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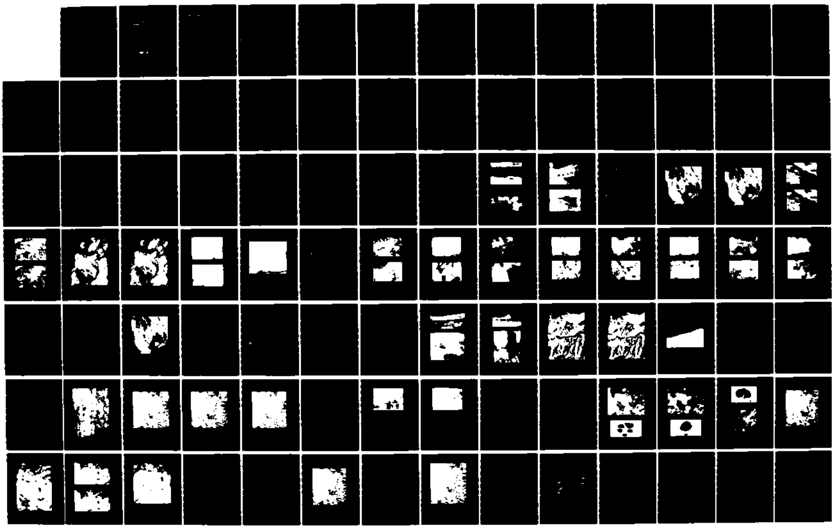

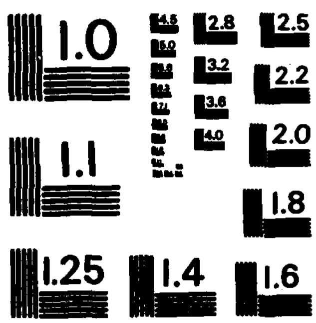

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Coso: Example of a Complex Geothermal Reservoir

by
Carl F. Austin
and
William F. Durbin
Public Works Department

SEPTEMBER 1985

NAVAL WEAPONS CENTER
CHINA LAKE, CA 93555-6001

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Naval Weapons Center

FOREWORD

This document presents material that is a part of a continuing applied research program investigating the geothermal energy potential of Navy lands. Using the geothermal system at Coso as the site for reservoir interpretation and modeling will enhance the development of the Navy geothermal resource at Coso and will enable the timely testing of both new and traditional geothermal reservoir concepts. This study was funded during fiscal year 1985 under Task No. Z0829.

This publication was reviewed for technical accuracy by James A. Whelan of Code 266, Naval Weapons Center, China Lake, Calif., and James L. Moore, Vice President, Exploration of California Energy Co., Inc., Santa Rosa, Calif.

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(U) The Coso geothermal system has been widely studied and reported by scientists through the past several years, but there is still a considerable divergence of opinion regarding the structural setting, origin, and internal structure of this energy resource. Because of accelerating exploration and development drilling that is taking place, there is a need for a reservoir model that is consistent with the limited geologic facts available regarding the area. The model should be one that is compatible with geologic theory and facts tested at similar locations worldwide, and that provides a reservoir model that gives drilling targets and productivity estimates that can be tested as the resource is developed. Like virtually all resources, Coso will be drilled and tested and well into production long before controversies over origin and structure are settled. This paper presents a model of the Coso reservoir that treats the reservoir as a complex assemblage of linear brecciated fracture zones, brecciated fracture intersections, vertical breccia pipes, and fracture networks that spread upwards. An ability to recognize the possible presence of each of these fracture zones from surface evidence will facilitate evaluation of the overall Coso reservoir system, as well as aid the identification and evaluation of reservoir components in other similar geothermal deposits. An understanding of the subsurface geometry of these reservoir components is critical in planning field development and in estimating productive capacity and life of individual producing zones.

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INTRODUCTION

The Coso geothermal system is a complex geologic feature on Naval Weapons Center land in eastern central California (Figure 1). This geologic feature has a prominent surface expression in the form of perlite domes, steam vents, and hot springs that has long caught the attention of prospectors and developers. Figure 2 shows the view of the perlite dome field that prospectors and miners of the Coso mining camp would have had from Silver Peak. Indeed, one such early prospector, on returning to Visalia, which at that time was the supply center for the mines at Coso (generally now called Old Coso as opposed to Coso Hot Springs or the New Coso Mining District which is now called Darwin), described the area as follows:

> " . . . sterile and waterless except for boiling springs . . . . " He further noted that " . . . About 20 miles to the southward of Silver Mountain the party visited an active volcano. On some of the cliffs in the neighborhood of the volcano were found sculptured and painted figures, the latter colored with some pigment, perhaps cinnabar." (Reference 1.)

In 1876, roughly the same time as the description above was written, a small hot spring in the vicinity of Little Lake (Lagunita) was noted by Wheeler in his report on areas west of the 100th meridian (Reference 2). We also can follow the development of commercialization at Coso, from the time it was called "Hot Mud Bank," to being called "Mud Springs," and finally to today's appellation of Coso Hot Springs. Economic interest in the area vascillated between hot spring resort development (Figure 3) and mining development (Figure 4). The early history of the area is well discussed in Reference 3. Mining activity during the first half of the 20th century included attempts to produce mineral water, therapeutic muds, mercury, perlite, pumice, gold, and tungsten. Pumice is still being produced (Figure 5).

Speculation over the potential for geothermal power production and the types of fluids that might be present at Coso was expressed by Austin in 1963 (Reference 4). In 1964 Austin discussed the following:

> "In summary then, the Coso Thermal Area has an excellent steam potential and has some potential for underlying brines of an intermediate composition. These brines will tend toward siliceous fluids near the surface, and will probably show increasing potassium with depth." (Reference 5.)

Also in 1963, in an unpublished manuscript of the U.S. Geological Survey (USGS), W. K. Moyle, Jr., estimated the power potential of several of the flowing steam wells left from the former Coso resort operations. However, he limited his reservoir discussions to possible heat accumulations beneath alluvial fan gravels cemented into cap rock by spring deposits. As a result, Moyle expressed the opinion that only the deep alluvium east of the Coso resort could serve as a possible geothermal reservoir and that the widespread areas of granite outcrop were not suitable as a reservoir. This opinion is still widely held and expressed by people not familiar with the processes of brecciation and ore deposition within crystalline host rocks.

In 1971 the Naval Weapons Center published a report that proposed the development of a number of geothermal deposits of different types, one of which was a magmatic heat source system as exemplified by Coso (Reference 6). In this widely reprinted generalized model of Coso, it was hypothesized that upward apophyses or cupolas in the hood of the magma chamber would result in the transport of both heat and fluids to drillable depths. Since the publication of that paper, which marked the real beginning of the Navy geothermal program and the serious development of Coso for power, an extensive body of technical literature has been published both on specific features of the geothermal resource area, such as depth to magma, and on general or generic features of the resource area as a whole. The most comprehensive accumulation of papers on Coso appeared in the *Journal of Geophysical Research* in 1980 (Reference 7). Despite the rather voluminous amount of material published on the Coso geothermal system, there remains at this time a considerable amount of disagreement as to the geologic setting for Coso, the general structural pattern, and the origin and position of the magma. What these disagreements represent are interpretations based on differing geologic philosophies as to regional structure, the origin of magmas, and other such issues.

THE GEOLOGIC SETTING

The Coso geothermal area appears on satellite photographs as a nearly circular feature, with a diameter of approximately 20 miles. Figure 6 shows the location of the satellite photograph, which is shown unretouched in Figure 7. The photograph is shown again in Figure 8 with the major geologic and geographic features of interest delineated. Various factions have questioned whether or not the Coso geothermal system is actually outlined by arcuate fractures. Figure 9 is an unretouched photograph taken at high altitude and looking south along the west edge of the Coso geothermal system. Figure 10 is the same photograph showing the arcuate fracture proposed by Austin and shown on Duffield's map published by the USGS (Reference 8). Of a more controversial nature is whether or not the arcuate fracture pattern seen in the Sierra to the west continues through the granitics of the Coso Range to the east. If this is so, there may well be a genetic significance to the size of the circular feature being outlined and to the angle of inward dip. If the arcuate fracture pattern does not cut the granitics of the Coso Range, then one could build a strong argument that the arcuate fracture seen in the Sierran granites represents a slump whose position is fortuitous with respect to the energy resource located at Coso.

Figure 11 shows a high-altitude photograph taken looking over the northeastern portion of the Coso geothermal system. Figure 12 shows this same photograph with two prominent, arcuate, concentric, inward-dipping fractures located in the proper position to represent the continuation of the arcuate system of the Sierran side of the Coso resource area into the granitics of the Coso mountains. Our interpretation is that the inward-dipping arcuate-fracture pattern (roughly 20-mile diameter by 65-degree inward dip) represents the surface signature of a body of magma that has undergone periodic vertical motion and pressure spikes because of the accumulation of water and other volatiles in the uppermost portions, especially in cupolas or apophyses. The depth to the main magma body at Coso has recently been reviewed by Goldstein and Flexser as a part of an ongoing search for shallow magma bodies (Reference 9). They cite various opinions that place the magma at depths between 5 and 8 kilometers, but it is obviously possible for cupolas or groups of dikes to extend upward to shallower depths. Temperature logs and seismic data suggesting that magma may be as close as 3 kilometers from the surface has also been noted in the literature (Reference 10).

DATING THE FEATURES AT COSO

Whether or not magma or some sort of crystal mush is present below the main dome field today may be arguable; but the simple fact remains that a large number of perlite domes, vents, and probable vents are present, testifying to the recent nature of the vulcanism within the Coso geothermal system. The USGS has presented dates for a number of the perlitic dome features at Coso, dating approximately 37 domes with ages ranging from slightly over 1 million years to 44,000 (± 22,000) years before present (YBP) (Reference 7). Our detailed interpretive studies show at least 61 perlitic eruptions and a minimum of 41 surface features that are considered eruptively suspicious; i.e., there was no vent formed in the classic sense. Rather, there is a localized fracture and alteration pattern indicating that the locale was stressed or damaged by processes involving hydrothermal fluid migration or shallow steam accumulations. The published age dates present the explorationist with two anomalies to consider when attempting to pinpoint drilling targets: the clustered nature of the eruptions and the lack of erosion on the sides of many of these eruptions.

Because of the clustered and overlapping nature of many of the perlitic domes, there is a high probability that early material is reused repeatedly in subsequent dome and pumice ring formation. Thus, unless a sample is taken with great care and understanding, there is a chance that the resulting age date will be rather unrelated to the age of formation of the specific volcanic features under study. Sugarloaf is a good case in point. Figure 13 is a blowup of an unretouched photograph of the Sugarloaf area and Figure 14 shows the probable outlines of coalesced domes (ignoring the mechanics of which overlaps which). Thus, we see that Sugarloaf represents a complex of at least 20 exposed domes or vents, some of which would appear to involve no new volcanic material at all, and others of which, unless truly simultaneous, must be made up largely of their neighbors' rocks and debris.

The second problem one encounters when evaluating age dates is how to reconcile the crisp freshness of many of the domes with the climates of the recent past. Consider the extrusive features seen in Figures 15 through 17. In Figure 15 we see an old, deeply eroded, extrusive feature dated at 1,040,000 YBP by the USGS (Reference 7). With the extent of devitrification and erosion, such a date is certainly believable. In Figure 16, we see a more subdued structure, dated by the USGS at 244,000 (± 28,000) YBP, and on which the ravages of erosion are obvious. The volcanic features shown in Figure 17, however, are quite different. In this figure we see a crisp, clean perlite dome dated at "less than 100,000 years old," yet the region had to have been subjected to both the Tioga stage pluvial period of nominally 4,000 years ago and the Tahoe stage pluvial period of nominally 10,000 years ago, as well as to the pluvials that are presumably associated with the major Pleistocene Lake stands of the region (Reference 11). The 10,000-year age for the Tahoe stage pluvial period and the 4,000-year age for the Tioga stage pluvial period are further supported by the work of Antevs. He describes the beginning of a post-pluvial period at 10,000 YBP and notes the re-birth of Owens Lake (ostensibly from a pulse of pluvial activity at the end of the "Long Drought" period from 7,500 to 4,000 YBP) during the middle post-pluvial period of approximately 4,000 YBP (Reference 12). Additional works challenge these ages for the Tioga and Tahoe glacial-pluvial periods. Norris and Webb list the ages of the Tioga and Tahoe glacial periods at 20,000 and 50,000 YBP, respectively. They list a series of glacial periods younger than Tioga and a number of older ones including the Casa Diablo period at 400,000 YBP, the Sherwin period at 750,000 YBP, the McGee period at 1,500,000 YBP, and the Deadman stage at 3,000,000 YBP (Reference 13). Even with the older conservative dates for the Tioga and Tahoe pluvial periods, the perlite domes should have undergone extensive exposure to erosional forces if the USGS dates are appropriate. Table 1 shows the ages and relative intensity of glacial-pluvial

activity, and the published age dates of the perlite domes. We believe that the age dates need to be thoroughly re-evaluated as to exactly what was being dated by the samples collected.

TABLE 1. A Comparison of Glacial-Pluvial Activity With the Published Age Dates of the Perlite Domes at Coso.

The columns are independent of one another. The entries in each have been spaced according to date.

Glacial-pluvial age (Reference 12)		Glacial-pluvial age (Reference 10)		Glacial-pluvial age (Reference 11)		Perlite dome age dates in years[a] (Reference 7)
Name of period	Years before present	Name of period	Years before present	Name of period	Years before present	
Matthes	0-650					
Unnamed	1,000	Middle post-pluvial "pulse"	4,000	Tioga	4,000	
Recess Peak	2,000-6,000					
Unnamed	6,000-7,000					
		Post-pluvial beginning	10,000	Tahoe	10,000	
Hilgard	11,000					
Tioga	20,000					
Tenaya	26,000					
						44,000 ± 22,000 (Sugarloaf)
Tahoe	50,000					
						57,000 ± 16,000
						72,000 ± 31,000
						81,000 ± 8,000
Mono Basin	87,000					
						88,000 ± 38,000
						90,000 ± 25,000
						90,000 (OHR)[b]
						93,000 ± 26,000
						99,000 ± 72,000
						101,000 ± 33,000
						160,000 (OHR)[b]
						235,000 (OHR)[b]
						244,000 ± 28,000
Donner Lake	250,000					
						265,000 (OHR)[b]
						293,000 ± 35,000
						399,000 ± 45,000
Casa Diablo	400,000					
						560,000 ± 24,000
						587,000 ± 18,000 (South of Devils Kitchen)
Sherwin	750,000			Sherwin	750,000	
						1,040,000 ± 20,000 (North of hot springs)
McGee	1,500,000					
Deadman	3,000,000					

NOTE: Readers are referred to any standard historical geology text, such as Dunbar and Waage, for additional information on Pleistocene glaciation.

[a] Potassium-Argon age dating unless otherwise noted.

[b] Obsidian hydration rind (OHR) age-dating method.

THE BASEMENT RIDGE

The very impressive perlite dome field of the Coso geothermal system is perched on and along the side of a prominent granitic ridge that is slightly offset to the east with respect to the rather circular outline of the geothermal field noted earlier in Figure 8. Duffield, Bacon, and Dalrymple stated in their paper:

> " . . . Vents for the volcanic rocks of the younger period are localized on and near a host of basement rocks within a concavity defined by the distribution of vents of the older period. The alignment of many vents and the presence of a considerable number of roughly north-trending normal faults of late Cenozoic age reflect basin and range tectonics dominated by roughly east-west lithospheric extension . . . ." (Reference 7.)

This basement ridge is the host to whatever commercial reservoir complex may be present. When studying and interpreting the geology of this ridge, one must recognize it is a complex mixture of (1) older metasediments, intrusives, and dikes; (2) the superimposed mineralization, fracturing, and hydrothermal alteration of these older intrusive systems; (3) the younger hypabyssal dikes, plugs, and necks of the Coso perlite dome field; (4) the dikes or plugs that feed the young basalt flows; and (5) the hydrothermal alteration, fractures, and mineralization associated with the presently active geothermal system itself.

Many of the major rock types of the geothermally attractive area (from a commercial exploration viewpoint) were described in 1962 by Austin and Pringle who did extensive thin-section studies of many of the rocks occurring at the Naval Weapons Center (Reference 14). Major rock types of the basement reservoir host at Coso include quartz diorite, granodiorite, granite, and leucogranite, as well as dikes of these materials and some dark, coarse materials interpreted by Austin and Pringle as metasediments. The map of Figure 18 shows locations of the samples studied. Table 2 presents generalized descriptions of the rocks of the central basement ridge that provides most of the basement reservoir host for the Coso geothermal system. Figures 19 through 22 show photomicrographs of typical samples of these materials.

TABLE 2. Properties of Typical Basement Rocks at Coso.

Properties	Rock type			
	Diorite	Granodiorite	Granite	Leucogranite
Dark minerals, %	5 to 50	5 to 50	5 to 50	0 to 5
Plagioclase feldspar composition	Oligoclase to andesine	Oligoclase to andesine	Oligoclase to andesine	Oligoclase to andesine
Potassium-feldspar of total feldspar content, %	5	5 to 35	65 to 95	65 to 95
Quartz in total quartz-feldspar content, %	5	5 to 50	5 to 50	5 to 50
Density	2.72 to 2.99	2.67 to 2.79	2.56 to 2.74	2.56 to 2.74

COSO MAGMA

The origin of the Coso magma and the interpretation of the properties of this magma as a heat source, the magma being both a source of fluids and a "pump" for driving localized Van Hise convection cells (Reference 15), is subject to the usual philosophic controversies that have been with geology for generations. The controversy swirls about the interplay of differentiation and granitization; i.e., differentiation of essentially basic magmas to yield the rhyolitic extrusives, and granitization, representing intense mid-crustal metamorphism to yield a crystal mush when water accumulation occurs. This controversy is a fascinating philosophic argument and could conceivably be resolved someday by very deep drilling at Coso. However, the only immediate effect this issue has on reservoir modeling above the magma hood itself is on the estimation of water volume available without exterior recharge, and on the trace element chemistry, including some isotope signatures.

We subscribe to the theory of mid- to upper-crustal granitization. This theory states that mobility in the melt is the result of water accumulation; and mobility loss is the result of water loss during eruptive events, while temperature in the magma chamber, and, more important, in the upper apophyses or cupolas, remains virtually constant. This concept is important. The pulses of extrusive activity at the surface reflect the accumulation of volatiles (these being largely water) within a relatively shallow zone of heated rock. During an eruptive cycle the viscosity of the magma is not controlled by temperature. To rapidly heat or cool masses of rock measured in terms of cubic miles of volume is physically impossible; thus, the variation in volatile content and its effects provide a logical hypothesis for the multiple eruptive phases seen at Coso. This variation is characterized in Figure 23 and is described in the classic paper of Kennedy (Reference 16) and in Roedder's description of classic vapor-pressure relationships* (Figure 24).

Since it appears that the Coso geothermal field is still underlain by viable magma, the main energy system (i.e., magma system) should once again be accumulating water and building pressure. This accumulation should cause the leakage of fluids from the magma to increase. Likewise, heat transfer should increase as well. One could argue that Coso has had its last eruption. Apparently, however, there still is magma at modest depths beneath Coso; thus, there should be increasing pressures and upward flow so long as the upper magma chamber remains hotter than the surroundings, even if the point of vesiculation and hood fracturing is never reached again. The magmatic conditions at Coso appear to be ideal for maintaining deep reservoir recharge.

STRUCTURAL SETTING

The structural setting for Coso, like all of the other aspects of this great deposit, excites controversy based to a great degree on the geologic philosophy of the individual investigator. The first comprehensive attempt at defining a structural setting for the Coso geothermal system was that of Austin, Austin, and Leonard (Reference 6). Their concept was that of an intrusive formed in the obtuse side of a fault intersection, a common setting for intrusive systems. This fundamental control of the intrusive is illustrated in Figure 25, which shows a northwest trending en echelon feature offsetting the Sierran block. Other investigators, such as

* Edwin Roedder, personal communication with Carl F. Austin, 1954.

Roquemore, invoke more diffuse and complex fracture settings (Figure 26 (Reference 17)). Duffield, Bacon, and Dalrymple state their interpretation in summary:

> "This system apparently is heated by a reservoir of silicic magma at 28-km depth, itself produced and sustained through partial melting crustal rocks by thermal energy contained in mantle derived basaltic magma that intrudes the crust in response to lithospheric extension." (Reference 7.)

Prior to the drilling of the discovery Well 75-7, which produces some 180,000 lb/hr of steam at a reservoir temperature of 415°F, Austin, who was recommending Coso as a good steam prospect, was deluged with opinions stating that a crustal extension was occurring at Coso and no heat of significance should be expected in such an area. On the other hand, Duffield, Bacon, and Darymple, in their above quotation rely on crustal extension to account for the heat transfer process itself. It is interesting that no one has come forth with a model for the formation of the Coso geothermal system based on the abundant compressional features of the area. The most notable of these features are (1) the Slate Range anticline (Reference 18); (2) the anticline of the Argus Range; (3) the Davis thrust of the Darwin hills (Reference 19) and the stress field that clearly controls the ore deposits at Darwin; (4) the thrusts of the Talc City Hills (Reference 20); and (5), of a more regional nature, the thrusts of southern Death Valley, which is a set of stacked thrust sheets and not a graben (Reference 21).

Authors such as Hopper, at least in passing, note the possibility that the Coso Range is a warp, rather than of simple fault origins. Hopper states that:

> "The dips of the Coso formation . . . suggest that the latest uplift of the Coso Range . . . may have involved broad anticlinal flexing . . .
>
> "It might even be postulated that, just prior to the faulting by which the present topography is so largely determined, the late Pliocene or early Pleistocene erosion surface was flexed into a great north-trending warp whose axis was near the site of the present Coso Range and which included as its west and east flanks the Sierra Nevada and the Argus Range respectively. The faulting between the summits of the Sierra Nevada and the Argus Range could then be regarded as the result of the later collapse of the crest of this great anticline." (Reference 22.)

Thus, in Figure 27, the regionally prominent compressional features are plotted in relation to the Coso geothermal system. Figure 28 shows the stress field that appears to have controlled the fractures in which the ore deposition occurred in the main ore deposit of the New Coso Mining District (Darwin Mines). Because the en echelon zone of fractures (locally called the Wilson Canyon fault zone) is parallel to the Darwin Tear Fault of Figues 27 and 28 and has the same sense of motion, it is a useful exercise to consider the orientation of the mineralized fractures in the region of the Wilson Canyon fault as well. Figure 29 presents the orientation data for the several classes of mineralized fractures from this area (Reference 23). These fractures, especially the prominent compressional features, raise fascinating questions over what is the exact structure of the Sierra Nevada in the vicinity of Coso. Is it truly the rotated fault block it is popularly assumed to be or is it a thrust sheet with frontal slumps?

The structural pattern and setting of the Coso geothermal deposit will no doubt be argued for decades to come. Certainly, exploration and development will proceed regardless of the ideas espoused in the scientific press, since a discovery has already been made. The structural and reservoir theories must continually be re-evaluated as more data becomes available from present- and deeper-level drilling. One must also remain aware that accumulations of mineral material and heat are anomalies, and as such may be the result of unique localized conditions superimposed on the traditionally assumed regional setting. The principal use of theory and model at Coso, at this stage, is to provide predictions that are geologically reasonable, are within the laws of physics, are of a probable economic nature, and that will improve the odds for success as exploitation and development proceed. The models used at Coso will be useful even if they only provide encouragement and the theories are only partially correct.

THE DEVELOPMENT HISTORY OF COSO

The development history of Coso in a modern sense can be considered to have begun with local interest in what was then called simply "Hot Mud Bank" on the early maps of the region. This name later became "Mud Spring," obviously not a name to inspire developers and visitors. In more recent times the area became known as "Coso Hot Springs." At the time the Navy acquired the area it consisted of a cluster of shacks, tent cabins, and a few permanent buildings adjacent to numerous drilled and dug wells and ponds. The original "mud spring" cannot be located today, but the term "hot mud bank" describes nearly a mile of what is the scarp of the so-called Hot Springs Fault. Both topography and geology support the idea that the original "mud spring" would have been at the location of the dug pond south of the present resort structures, but this cannot be verified. In addition to resort development (Figure 30), prospecting and mining altered the main fumarolic areas as mercury and sulfur were sought. Thus, what is now called the Devils Kitchen was an open pit mine developed to feed the mill shown in Figure 31. The steam in Devils Kitchen comes almost entirely from shallow drill holes put in to explore for mercury (Reference 24) as does the bulk of the steam at the Nicol (Basin) mercury and sulfur mining area and at the Wheeler mercury mining area.

NAVY TESTING FOR RESERVOIR CONDITIONS

In 1966, the Navy sought geochemical data that would allow an estimate of "reservoir conditions" at Coso. To gain a fluid sample from below the zone of oxidation, a well (Coso No. 1) was drilled into the footwall of the Hot Springs Fault. The results of this shallow drilling program are presented by Austin and Pringle (Reference 25) and the well is shown in operation in Figure 32. Coso No. 1 lends credence to the concept that pluvial periods of the area probably significantly affected the upper portions of the Coso reservoir system.

A perusal of the logs of Coso No. 1 reveals the presence of definite former surface zones as red oxidized layers. The upper two layers should represent the two most recent pluvial periods, the Tioga and the Tahoe (nominally 4,000 and 10,000 years ago respectively, according to widely used traditional values), although Table 1 presents alternative age dates of various authors (References 10 through 12). Coso No. 1, drilled to be in the footwall of the hot springs fault, showed one red oxidized "soil" horizon from the surface to 3 feet, one from 85 to 120 feet, one from 153 to 166 feet, and one from roughly 275 to 280 feet. If we assume the red weathered granite fill on the Coso fault to represent the end of pluvial periods, then there would appear to have been major erosional action and valley filling associated with Tioga time

(82 feet of fill) and with Tahoe time (33 feet of fill). Some of this fill is undoubtedly related to motion on the hot springs fault, but the implication is that there has been extensive erosional activity in the area during pluvial periods. The red zone from 153 to 166 feet is interpreted as the post-Casa Diablo soil, which is overlain by 21 feet of post-pluvial erosional fill. The same situation is seen in a typical dug water well in a brushy flat in the Sierras to the west, where a 2-foot soil horizon with artifacts occurs 3 feet below the present surface, and a soil horizon with root holes and animal burrows occurs at 18 to 20 feet from the surface.

EFFECTS OF PLUVIAL PERIODS

As a result of the various pluvial periods of the past, massive flooding of the upper portions of the Coso geothermal system and the attendant periodic flushing out of the shallow chemical components should be the norm. Two lines of evidence are involved when one attempts to estimate the volumes of fluids exchanged in such periods. The first of these would be the volumes of saline and bitter minerals in selected layers of saline minerals in Searles Valley. Most popularized publications refer to leaching of country rock as the source of salts in bitter lakes. However, the presence of a chain of lakes and a drainage pattern leading from the well-studied Long Valley caldera to Searles Lake gives credence to the possibility that the Long Valley area is a major source of bitter salts in the Searles Lake basin (Reference 26). This hypothesis must be modified on chemical grounds (low arsenic in Searles Lake), as well as on the results of more recent geothermal exploration that shows both heat and various brines at Owens Lake, at Coso, in Indian Wells Valley, and in Searles Valley itself. All of these geothermal systems should have contributed to the Searles Lake "world class" salt and brine deposits. It is hoped that as the chemistries of each of these discrete geothermal deposits are better understood, the geochemical differences between them will enable the identification of the contribution of each of these sources to the Searles Lake deposits. As an example, the Long Valley system is relatively high in arsenic* and Searles Lake is relatively high in tungsten (Reference 27). The entire chain of geothermal deposits in this area appears as an extension of the arsenical gold belt proposed by Joralemon (Reference 28). Since Searles Lake is relatively low in arsenic, Long Valley, which is quite high in arsenic, is unlikely to be the major contributor of salts to this basin, nor is any other arsenical geothermal deposit. The Coso geothermal system has not been found to be especially high in arsenic, so it should still be considered a major possible contributor to the Searles Lake saline deposits. Another element to look for is tungsten, probably located in the deeper original brines at all of these upstream geothermals (note that the surface of any of the brines may have been extensively flushed out). Given a trace element tie, an estimate could then be made of the volumes flushed out and, with deeper drilling, an estimate could be made of the depths of flushing.

The second line of evidence to pursue in estimating the volumes of fluids exchanged in pluvial periods must begin with determining the degree of probable floodings in Rose Valley, which raised the hydraulic gradient eastward through the Coso geothermal system. Figure 33 shows a portion of a satellite photograph of the south end of Rose Valley, which is the drainage exit. The two prominent features are a basalt-filled river channel and the landslide that dammed the valley outflow and is still largely responsible for the ponding of Little Lake. A recent paper discussed the basalt-flow-filled channel briefly (Reference 29), but does not address the landslide phenomenon. Figure 34 shows a side view of this well-formed and

* Personal communication between Raymond Derby and Carl F. Austin, 1963.

prominent landslide. Since water chemistry shows that Little Lake does not draw on Rose Valley groundwater, except for a small fraction, it is extremely probable that the major drainage out of Rose Valley is maintained by the flow friction in the fracture debris of the landslide itself, and by the flow friction of the gravels beneath the landslide (hence the control of the hydraulic gradients into the Coso geothermal system). Indeed, were it not for this slide and the resulting blockage of the drainage of Rose Valley, the temperatures of the Coso resource would be much more uniform, and the east side of Rose Valley would be heavily contaminated with reservoir fluid leakage, as is the Coso basin to the east. Instead, the ponded water in Rose Valley, combined with the high hydraulic gradients out of the Sierras, keeps Rose Valley largely fresh water and displaces the geothermal system eastward. If the formation of the Rose Valley slide was recent, it could have caused a sudden surge of flushing of the shallow portion of the early geothermal system simply by blocking the formerly somewhat deeper channel out of Rose Valley, and by ponding some of the younger basaltic lavas as well. This ponding would have caused temporary added increases of the hydraulic gradient going into the developing geothermal system, a possibility supported by the reported age of 140,000 years for these basalts.

Based on the belief that pluvial activity had critical effects on the chemistry and form of the Coso geothermal system, Moore, Austin, and Prostka stated in 1984 at the Third Circum-Pacific Energy and Mineral Resources Conference:

> "Although the Coso area at present lacks a shallow ground-water zone, one must remember that during the past million years of shallow, silicic magmatic activity, the area has had repeated, extensive ground-water accumulations as a result of pluvial periods. In actuality, the cyclic shallow activity has favored the formation of a thick argillitic seal rather than an extensive precipitation of minerals in fractures, so that a very open reservoir results beneath the argillitic capping." (Reference 30.)

Moore and Austin stated in 1983:

> "The main convective plume identified to date is probably only one of several present within this structure. It is centered 1 to 2 km east of the center of the apparent shallow silicic intrusion that has been identified to date (Figure 3). This effect may in part be due to the eastward regional groundwater flow (Figure 3), which, especially during the two most recent pluvial periods, should have flushed the shallow upper geothermal systems with massive amounts of recharge fluids. This cold water drive from the west with present day gradients eastward of 300 feet/mile has clearly skewed the rising geothermal plume eastward. With present lessening of the rate of recharge, the system should be reheating toward the west and upwards once again as the system recovers from the effects of the most recent pluvial period of nominally 3000 to 4000 years ago." (Reference 31.)

Figure 35 presents the schematic cross section of the Coso geothermal system that is described in the two prior quotations and that is based on the work by Fournier and Thompson (Reference 32).

DRILLING APPROACHES

After this rather voluminous geologic review, which is intended to set the stage for an interpretation of the reservoir at Coso, there is one further consideration the explorationist should evaluate. This factor is whether to "sharpshoot" specific drilling targets or to drill on a grid pattern. In many oil fields, drilling on a grid pattern would have been as good or better than the actual development that was based on geologic interpretation in advance of drilling. The choice between these two methods is a continuing controversy, whether drilling for oil and gas or seeking hard mineral deposits or their depositional predecessor, the geothermal system. This philosophic conundrum of exploration will not be pursued, other than to note that it exists (Reference 33). There is a strong body of evidence for sharp lateral discontinuities in productivity. We believe that a scattergun approach to the Coso geothermal system will get production, but will largely miss the major finds. We hope that the reservoir hypotheses presented in the remainder of this paper will encourage the sharpshooter to drill with a purpose in mind, for we believe it is this person who will fully develop the wealth of the Coso reservoir.

THE RESERVOIR

In an early attempt to determine the possible location of the producible reservoirs of the Coso geothermal system, in 1963 Austin prepared a series of lineation and fracture maps of the central portion of the Coso geothermal area. These maps were based on topography as an expression of weathering rates that in turn enabled plotting of zones of microfracturing, hydrothermal alteration, and silicification since these natural processes form linear hard and soft zones. Using these maps was considered to be a possible method of identifying fracture and breccia-zone reservoir components. The best of these lineation maps is reproduced in Figure 36. Although not previously published, this 1963 lineation and fracture study was the basis for the map (Figure 37) that was prepared to show the margin of what was then considered the prospectively valuable thermal area that was discussed in Reference 5. This map has been the general basis for the location of the boundaries of the Navy contract lands to ensure that the Navy would be the major thermal equity owner at Coso, and it has been the basis of much of the drilling done in the area. As a historical note, the early versions of these lineation and fracture maps were prepared by Austin for a subsidiary of Keevil Mining Group, Ltd. of Toronto, a pioneering company in the field of geothermal exploration who gave permission for the Navy to use them in 1964. In an expansion of the work done for Keevil Mining Group, Ltd. that was published as an updated Navy paper (Reference 5), a further attempt to determine if the Coso geothermal area contained identifiable drilling targets was carried out by Austin, Austin, and Leonard and was published in 1971 (Reference 6). In this study the authors attempted to separate the welter of overlapping fractures and the alteration and metamorphism patterns from those features that would indicate a resource within a drillable distance of the surface. The exploration philosophy behind this study is expressed as follows (the resulting map is shown as Figure 38):

> "The location of the controlling or primary magma system can be readily observed on high-altitude photographs in the form of closed arcuate patterns in the form of ellipses comprised of fracture, alteration, intrusion and

collapse patterns. These primary magmatic chamber patterns range from 25 to 30 miles in length and 15 to 20 miles in width. Within the controlling primary pattern are smaller patterns generally 4 to 6 miles in diameter. These smaller circular to elliptic patterns are believed to represent the surface expression of underlying stocks and apophyses of stocks, and mark the active geothermal cells suitable for exploration." (Reference 6.)

The successful drilling of Well 75-7 as the discovery well makes interest in delineating reservoir targets and sizes more timely, especially since the performance of Wells 75-7, 71-A7, and 31-8 are so obviously different. Table 3 presents a summary of the characteristics of these three wells. This apparent difference becomes even more striking when one compares Wells 15-8 and 16-8. Well 16-8 is a prolific producer, yet only 375 feet away Well 15-8 is at best a marginal producer with comparable mass flow but markedly lower temperatures. Table 4 presents a comparison of these two adjacent wells.

TABLE 3. General Characteristics of Wells 75-7, 71-A7, and 31-8.

Measurements are in milligrams per liter unless otherwise stated.

Parameter	75-7 (7-6-82)	71-A7 (5-12-82)	31-8[a]
pH units	7.6	8.18	8.5
Electrical conductivity	13,000 μmhos/cm^2 (5-12-82)	10,000 μmhos/cm^2	N-A
Total alkalinity	59	N-A	N-A
Carbonate alkalinity	0	14	N-A
Bicarbonate alkalinity	59	120	162
Chloride	4,500	3,300	3,230
Sulfate	26	62	130
Fluoride	3.8	4.7	N-A
Silica	600	260	320
Ammonia	0.40	3.2	1.5
Boron	97	N-A	N-A
Total filterable residue	8,200	6,000	N-A
Nonfilterable residue	290	N-A	N-A
Arsenic	21	7.7	N-A
Calcium	59	9.7	19.4
Iron	0.98	<0.050	N-A
Magnesium	0.24	<0.010	0.29
Mercury	0.00018	0.00034	N-A
Sodium	2,800	2,000	1,940
Potassium	440	340	210
Lithium	21	18	13.8
Sulfide	N-A	<1.0	N-A
Total CO_2	N-A	61	N-A

NOTE: N-A means the well was not analyzed for that parameter.
[a] Analysis performed by USGS and is not complete.

TABLE 4. Characteristics of Wells 15-8 and 16-8.

Measurements are in milligrams per liter unless otherwise stated.

Parameter	Well 15-8	Well 16-8
Calcium	31	18
Magnesium	0.54	0.06
Sodium	2,100	1,800
Potassium	190	320
Silica	370	580
Aluminum	0.6	0.29
Antimony	<0.01	N-A
Arsenic	8.2	8.8
Copper	<0.005	N-A
Iron	0.08	<0.05
Cadmium	N-A	0.02
Lithium	19	20
Manganese	<0.01	N-A
Mercury	<0.0005	<0.001
Thallium	<0.01	N-A
Zinc	<0.02	N-A
Lead	N-A	<0.01
Total alkalinity, as $CaCO_3$	80	...
Bicarbonate	80	110
Carbonate	0	N-A
Hydroxide	0	N-A
Boron	79	80
Bromide	4.4	N-A
Chloride	3,600	3,400
Fluoride	3	3.7
Sulfate	100	42
Nitrate, as N	<0.03	N-A
Nitrite, as N	<0.003	N-A
Ammonia, as NH_4	0.4	0.3
Total phosphate, as P	2.5	...
Specific conductance	N-A	11,000 μmhos/cm^2
Dissolved solids	9,700	6,400
pH units	N-A	7.5
Cation:anion ratio (percent)	93	...

NOTE:

1. N-A indicates that the well was not analyzed for that parameter.
2. Wells are located only 375 feet apart.

In an effort to provide a framework for more closely identifying reservoir components, Austin prepared a fracture map in 1985 that attempted to identify only those fractures that had a definite relationship with magmatic material transport. Those fractures that were probably related only to subsidiary effects of magma pulsations or magma chamber inflation and deflation were not included. Figure 39 is the base photograph used for plotting, Figure 40 shows the identified domes and vents (ignoring relative overlap of dome skirts), and Figure 41 is the resulting fracture pattern. The striking aspect of these fractures is that they converge in four nodal points; they do not form northerly, northeast, northwest, or any other form of conjugate sets, rather, they intersect, which gives us an added clue as to what may be occurring at depth and why the fractures formed. The most likely explanation is that vesiculation within four separate cupolas or apophyses resulted in expansion at depth with the formation of radial tensile fractures from the resulting hoop stresses.

This fracture network, combined with drilling results (with careful analogy to the many epithermal ore deposits explored extensively in volcanic regions of the world and especially in areas of relatively young vulcanism), has lead the authors to propose that the Coso geothermal system consists of a combination of four types of reservoir conditions. Granted, there is a degree of gradation between these conditions, but they can clearly be considered as separate identifiable groups of targets: vertical breccia pipes, fracture intersection breccias, linear breccia zones, and spreading fracture networks.

VERTICAL BRECCIA PIPES

The most prolific, productive zone for geothermal fluids one could expect to find in a granitic host rock, such as the Coso resource zone, would be a major vertical breccia pipe. Furthermore, if one such pipe is found to exist, there is a high probability that others will be present as well. One excellent description of the general characteristics of breccia pipe systems is that of R. T. Walker. The following quoted passages from Walker's paper "Mineralized Volcanic Explosion Pipes" (Reference 34) are printed with permission of McGraw-Hill, Inc.:

> "The holes blown through the earth's crust above a body of magma when the gas pressure at the top of the magma exceeds the strength of the crust at that point, are similarly pipe-like in form and hence are termed volcanic explosion pipes. [Also known as "maars" or "embryo" volcanoes].
>
> "The walls of these pipes are nearly vertical, although near the surface they tend to flare out and become funnel-shaped. The shape in cross-section is determined chiefly by whether or not the explosion took place along some pre-existing fissure. If it did, the shape is likely to be irregularly lenticular, with the long axis, following the fissure, often several times the short axis. Sometimes such pipes are so long and slender as to be almost dike-like in appearance. The pipes which have burst through unfissured portions of the crust usually vary from approximately circular to oval or eliptical in cross-section . . . .
>
> "The mean diameter may vary from less than 100 feet to more than 3 miles, but in the vast majority of pipes it ranges between 300 feet and half a mile . . . .

"Where the crust is weak and the magma is heavily charged with gasses, the explosion may occur when the top of the magma is more than a mile below the surface, thus creating a deep explosion pipe . . . .

"A noteworthy feature of volcanic explosion pipes is the relatively small effect produced in the surrounding formations; for although they are fractured and often upturned immediately adjacent to the pipe, they are usually undisturbed beyond a distance of 100 feet . . . ." (Reference 34.)

Within the pipe one can expect to find brecciated host rock, debris fallen in from above, and intrusive material from below. This material will be highly fractured by mechanical comminution and by autobrecciation, the latter causing especially angular fragments. In very large pipes, or in cauldron systems such as that of Cripple Creek in Colorado, one may even find sedimentation to have occurred, which indicates that some explosion systems can stand open for significant periods of time. It is also normal to expect a moat to build up around the mouth of a pipe or explosive eruptive center, although there are spectacular exceptions such as the main Cripple Creek system that has no eruptive material to account for the cauldron itself (Reference 35). Regarding the size of debris expected in breccia pipes of an explosive origin, Walker states the following:

"They vary in size from the finest dust up to blocks several hundred feet in length, although in most pipes it is uncommon to find pieces larger than 4 ft in diameter, and most fragments do not exceed 3 or 4 in." (Reference 34.)

The surface signature of complete or intact pipes that have vented significant amounts of gasses is described by Walker as follows:

"If the forces which have been responsible for the intrusion of the magma into the crust happen to have expended their potency at the time of the initial explosions, the pipe will remain filled with explosion breccia, and will be marked on the surface by a depression circled by a ring of debris. This will be distinguishable from a volcanic crater only by the fact that there has been no effusion of lava." (Reference 34.)

Of great interest to the explorationist or person who is attempting to estimate reservoir volume or reservoir productivity is the high probability that pipes of this type will occur in clusters at any given locality. Walker states the following:

"Volcanic explosion pipes filled with breccia, lava, or both, usually occur in groups. In some instances, apparently, an old vent becomes so solidly sealed that, with the resumption of magmatic aggression, another vent can be more readily created by the formation of a new explosion pipe in the vicinity. Or, since the sealing of the old vent, the magma may have made its way more closely to the surface somewhere else, so that the relief of gas pressure can more easily be obtained by the formation of a new explosion pipe at this point. In some areas underlain by large intrusive masses, the roof over the intrusive is perforated by many sporadically distributed volcanic explosion pipes, as if by a gigantic charge of buckshot. The multiplicity of pipes in such formations is probably attributable in principal part to the existence of numerous tongues or cupolas of magma extending upward from the main mass—each constituting a local reservoir for the accumulation of gas pressure, which ultimately is relieved by formation of a volcanic explosion pipe at that point, without affecting the others." (Reference 34.)

A superb example of the multiplicity of vertical breccia pipes occurring in a limited area is Red Mountain Pass in Colorado. At this location there are roughly 20 pipes, about 13 of which are mineralized, occurring in a 5-square-mile area described by Burbank (Reference 36). Figure 42 is a map of a portion of this classic breccia pipe area (modified from Fisher and Leedy (Reference 37)). Figure 43 is a photograph of the outcrop of the National Belle Pipe. The Crystal Hill area of Colorado is an example of a more dispersed group of pipes. Figure 44 is a map of the Crystal Hill area (Reference 38) and Figure 45 is a photograph of the Crystal Hill Pipe itself. This photograph shows in particular the knife-edge contact that can exist as the boundary of such a pipe. In this case, brecciation, alteration, and mineralization all stop in a matter of inches as one moves out of the breccia-filled pipe into the host rock.

Looking at the potentially productive area of the Coso geothermal system (Figure 37), one can search the surface for indications that vertical breccia pipes of some sort may be present. Certainly on theoretical grounds such features should be expected, both as isolated pipes or fracture intersection pipes. Looking back at Figure 40, it is not unreasonable to hypothesize that each of the major perlite domes sits atop a breccia pipe of some sort, or upon at least a fracture intersection type of breccia zone. This raises the question of whether or not ascending magma will consistently plug the entire conduit. Experience with breccia pipes that have been mined for their metal content shows that open breccia can surround magmatic material that has moved vertically through the pipe. This phenomenon can be accounted for by processes ranging from outward autobrecciation to simple vertical channeling because of lateral chilling or lateral fluid and gas pressure, depending on local circumstances.

Figure 46 shows an idealized plan view through a Red Mountain type of pipe and Figure 47 shows an idealized cross section (Reference 39) calling out the position of the intrusive present. These figures point out that the fractures, fracture intersections, and pipes beneath the perlite domes should not be discounted as drilling targets until considerably more exploration is done. At this time, there is no compelling reason to assume that the rising magma that formed the domes will have blocked the feeding conduits beyond the point of producibility. Furthermore, fracturing or chilling and autobrecciation could turn the magmatic filling into highly permeable zones as well.

The interpretation that a vertical breccia pipe system was a major potential reservoir component at Coso received strong support as a result of the drilling of Wells 75-7, 75A-7, 75B-7, 16-8, and 15-8 all of which delineate the margin of one pipe called herein the Condy Pipe. Wells 71-7 and 71A-7 are believed to be inside a second pipe called herein the Jim Moore Pipe. Figure 48 is a sketch of what appears to be the positioning of the pipes based on the drilling of the wells mentioned above. Figure 49 shows the actual location of these wells plotted on a photograph and the surface expression of the Condy Pipe. What we do not know at this stage is whether the producible portion of the pipe is a cylinder of breccia, or if it is a ring of breccia surrounding a less permeable volcanic neck type core; nor do we have any data at this time on whether or not such intrusive fill as is present in the pipe is fractured enough to be a significantly permeable portion of the pipe as well.

To illustrate the variations seen in mineralized breccia pipes, all of which are possible at Coso, we can turn to a paper by W. H. Emmons that gives a nice summary. He discusses the following:

> "1. Pipes and circles with closely spaced fractures, but with little rotation of fragments in the pipes. (Examples given include Kidston, Queensland; Alice & Jesse Pipes in Colorado; Mt. Morgan, Queensland; and the Altenberg stock of the Saxon Erzgebirgê).
>
> "2. Pipes in which there has been considerable rotation of material with brecciation and at places rounding of fragments in the pipes. The rounding of fragments probably resulted from movement of fluids in the pipes. Evidently gasses continued to pass through the pipes after they were blown out. (Examples given include Anna Lee, Bassick, Bull Domingo, Espiritu Santo, Cstâtye, and Rakosy near Veraspatámk.)
>
> "3. Another group closely related to group 2 includes the hollow 'cylinders' of ore, such as Los Pilares deposit near Nacozari, Sonora, and the Duluth Cananea pipe, near Cananea, Sonora.
>
> "4. Deposits that have formed in and around the vents of volcanoes. (Examples include Cerro de Pasco, Peru; Braden, Chile; Nagy Kirnik, Veraspatámk, Transylvania; Stan Trg, Trepča, Yugoslavia; and the Cresson pipe, Colorado.)" (Reference 40.)

The rock expelled from Well 16-8 in particular is subangular to rounded and is both altered and lightly mineralized with pyrite that is largely pyritohedral. We can, therefore, reasonably hypothesize that the reservoir unit composed of this breccia zone has been churned enough by gas- and fluid-flow to lose some of its angularity. Under the concepts of Lovering, the fluids present at the depth tapped by Well 16-8 are of the fourth stage noted in Table 5 (Reference 41). Thus, we should expect deeper fluids to increase in total dissolved solid content and to change with increasing depth to the fluids of the fifth stage, i.e., possibly higher metal contents. Table 6 presents the composition of the fluids from Well 16-8. Figure 50 is a photograph of ejected breccia fragments from Well 16-8, showing their generally rounded nature.

The authors have concluded from the evidence in hand that a vertical breccia pipe (the Condy Pipe), is the producing reservoir component for Wells 75-7, 75A-7, 75B-7, and 16-8. Well 15-8 is clearly outside of this pipe as is Los Angeles Department of Water and Power (LADWP) Well 43-7. (Pipes have been named to avoid the confusion of having multiple well designations referring to the same reservoir unit.)

The second vertical breccia pipe that has been identified is the completely independent feature named the Jim Moore Pipe. This pipe is the structure that was tested by Wells 71-7 and 71A-7. No wells nearby are outside of this pipe except for Well 31-8, which is nearly one-half mile to the east. We have no drilling data on the diameter of this reservoir component. However, a definite circular feature can be seen in an air photograph (Figure 51). This pipe gives fragments on start-up that appear totally different from fragments from Wells 75-7, and others, in the Condy Pipe. Two very different types of rock were expelled from Well 71-7. A

TABLE 5. Zoning of Hydrothermal Fluids According to Lovering Adapted From Reference 41.

Stage	Hydrothermal fluids in sediments	Hydrothermal fluids in volcanics and intrusives
Early Barren	Magnesian Chlorite	Magnesian Dellesite (Mg Chlorite)
Mid Barren	Argillic Kaolinite	Argillic Kaolinite
Late Barren	Silicification Cubic pyrite Jasperoid	Silicification Silicification Cubic pyrite Chlorite Barite
Early Productive	Potassic Sericite Hydromica Pyritohedral pyrite	Potassic Sericite Calcite Hydromica Pyritohedral pyrite
Productive	Ore Basemetal sulfides Au/Ag	Ore Basemetal sulfides Au/Ag
Post productive	Wurtzite—marcasite (may be highly acid supergene)	Wurtzite—marcasite (may be highly acid supergene)

TABLE 6. Composition of the Fluid From Well 16-8.

Analyte	Brine, mg/l	Condensate, mg/l
Sodium	1,800	0.55
Potassium	320	<0.2
Calcium	18	<0.1
Magnesium	0.06	<0.02
Lithium	20	<0.03
Iron	<0.05	<0.5
Lead	<0.01	<0.01
Cadmium	0.02	<0.02
Aluminum	0.29	<0.05
Arsenic	8.8	<0.02
Mercury	<0.001	0.004
Silica	580	<0.5
Boron	80	1.2
Chloride	3,400	1
Fluoride	3.7	<0.2
Sulfate	42	<1
Ammonia	0.3	2.0
Bicarbonate	110	<10
pH units	7.5	4.2
Specific conductance	11,000 μmhos/cm^2	40 μmhos/cm^2
Total dissolved solids	6,400	<5

NOTE: Separator 96 psig, 334 °F.

small amount of a hard, lightly altered, pink granitic rock with minor chlorite and cubic pyrite as shown in Figure 52 was recovered, suggesting that this well is involved with fluids of the third stage of alteration as defined by Lovering and will become more potassic with depth. A large amount, several dozen cubic yards, of white, intensely altered sericitized material with cubic pyrite was also ejected from this well on start-up (Figure 53).

The breccia fragments of the white altered material appear quite rounded, but in this case not only has there apparently been an extensive flow of gasses and fluids during and after pipe formation, but these fragments underwent extensive autobrecciation in spectacular fashion when the 71-7 Well was started for the first time. As the brecciated rock was ejected from the well, it would travel upward for a fraction of a second and then literally explode due to internal steam and fluid pore pressure. This phenomenon clearly shows that with this type of reservoir material, a rapid pressure drop caused by opening a well too quickly could cause extensive autobrecciation around the well bore and attendant well bore damage. This occurrence is a mixed blessing to the well operator. If autobrecciation occurs, the wetted perimeter of the well will expand, which will increase productivity, but the brecciation may require a liner which will itself reduce productivity because of plugging and added friction. Figure 54 illustrates the degree of fracturing one can expect with autobrecciation by showing an autobrecciated rhyolite.

Autobrecciation is a process that can convert a tight volcanic neck or dike into a highly permeable conduit or reservoir component. An important feature of breccia pipes seen in many mining districts where the pipes have become well exposed by mining activities is the apparent lack of lateral permeability in the upper few thousand feet of such systems. This means that communication between adjacent pipes may be very limited unless both pipes are on a major common fracture. As a result, at Coso, one would expect production in say, the Condy Pipe, to have a negligible effect on the adjacent Jim Moore Pipe since they do not share a common fracture. Furthermore, one would not expect heavy production in either pipe to significantly affect nearby wells outside of the pipes except for those in the pipe exhaust plume close to the pipe. Also, one would not expect activities in the pipes to have any detectable effect on the fumaroles and shallow wells of the old resort area a few miles to the east. This explains why the presence or lack of a steam cap in a given pipe does not mean adjacent pipes will or will not have one.

The Condy Pipe has a 300-foot-thick steam cap suggesting considerable shallow leakage as shown by the Devils Kitchen mineralization, while the adjacent Jim Moore Pipe does not appear to have a steam cap at all. This strongly suggests that a pipe with a steam cap underlies or "feeds" the Nicol area. However, although it is possible that a very small or limited steam cap could exist beneath the Wheeler area, the alteration zone is believed too limited to be encouraging to the authors of this report.

The Wheeler area is most apt to be the result of leakage from a "suggestive" structure just to the west. This type of structure will be discussed later in the text. Since pipes are expected in clusters, it is useful to estimate how many are present. An extremely tenuous initial estimate of the number of explosion-type, breccia-pipe drilling targets comparable in particular to the Jim Moore Pipe and to the Condy Pipe shows at least 18 such features present that should be tested. These targets are shown on the photograph of Figure 55. Each of the four nodal controlled fracture patterns has one or more associated possible breccia pipes. These possible pipes appear to occur at intersections of fractures from two nodes, with the pipes forming a north-northeasterly trending group of 14 possible pipes with a fairly regular interpipe spacing;

a second group of three possible pipes in a more northeasterly trend located slightly to the northwest; and a single isolated possible pipe associated with the northwesterly node. Selection of possible pipes (other than the Jim Moore and Condy Pipes already demonstrated by drilling), is based on indistinct circular eruptive features or indistinct "suspicious structures;" features with no obvious perlite domes (14 features), perlite domes with a surface expression comparable to the surface of the Condy Pipe (three features), and a bleached and discolored "suspicious structure" (one feature). The presence and positioning of these discrete reservoir elements is consistent with the findings of a ground-noise survey published in 1972:

> "The anomalies are clearly separated by stations that exhibit low power values indicating that they are individual reservoirs and not zones of high activity in one big reservoir." (Reference 42.)

The Condy Pipe appears to be the largest pipe in terms of its cross section as shown by the presence of a subdued perlite dome within a large prominent moat. As exploration continues, careful attention should be paid to whether or not the type of perlite dome, as shown by crater form or dome physiography, is an indication of the probability of an underlying permeable reservoir component.

Figure 56 shows (A) the type of eruptive associated with the Condy Pipe and (B) a dome similar to that of (A), but lacking the well-defined moat. Figure 57 shows an eruptive site with no extrusion, i.e., a typical breccia-zone surface signature. Figure 58 shows a common form of perlite dome at Coso with a relatively flat, lumpy surface and Figure 59 shows a perlite dome with an open crater. Each of these must, at this time, be considered the surface signature of a possibly different subsurface reservoir component. The location map and temperature data for a drill hole adjacent to an otherwise untested apparent pipe is shown in Figure 60.

FRACTURE INTERSECTION BRECCIAS

Making a distinction between isolated breccia pipes and the small vertical zones expected at fracture intersections may be somewhat arbitrary and indeed is really a matter of degree. Furthermore, there is no data at this time as to whether major perlite domes overlie breccia pipes of a major nature or perch on tight fracture intersections. The Coso geothermal system has a myriad of untested fracture intersections, any of which could be a brecciated conduit of high productivity. Figure 61 is a sketch of this type of reservoir component and Figure 62 is a map of those intersections that can be considered significant drilling targets. A total of 50 of these targets are proposed at this time. Only one such fracture intersection target has been drilled, that being the Wheeler site. Figure 63 shows a location map and temperature data for the drill hole. Bear in mind that the Wheeler site is close to a possible buried breccia pipe located just to the west.

A group of what we are calling "suggestive structures" are at the Coso geothermal system. These may be the tops of breccia systems or of an unrecognized structural element. Externally they strongly resemble features such as the top of the breccia pipe at Summitville, Colorado. Thirty-two such features are under study as potential targets of interest and of these, the most intriguing are shown in Figure 64. At this time we can say only that they represent tight arcuate fracture patterns covering less than a square mile and in most cases show moderate to strong hydrothermal alteration as well.

LINEAR BRECCIA ZONES

Continuing the gradational nature of the fracture and brecciation pattern at Coso, the opposite extreme to the isolated breccia pipe is the linear breccia zone. Any of the fractures of Figure 41 can locally be a linear fracture zone of higher than ordinary productivity caused by brecciation of the fracture walls, and can at any minor bend in the fracture provide a zone of favorable productivity. These linear breccia zones can be seen as so-called rubble dikes such as the Copper Fissure of the Darwin Mine immediately to the northeast or the well-known rubble dikes of the Tintic District (Reference 41). No drilling has identified a linear breccia zone comparable in potential productivity to a vertical breccia pipe such as the Jim Moore Pipe or the Condy Pipe.

SPREADING FRACTURE NETWORKS

An interesting aspect of the Coso geothermal field is the prevalence of upward spreading fracture networks that consist of deeper strong fractures that branch upward and spread out to the sides as the surface is approached. This type of reservoir component was first seen in detail in the Coso Geothermal Exploration Hole No. 1 (CGEH-1) where it became apparent in the cap rock that hydrothermal alteration was quite asymmetric, with the argillic alteration strong on the hanging wall, yet quite limited on the footwall as fractures were crossed. A very clear-cut example of this phenomenon is seen in the Amethyst Vein system of the Creede Caldera in Colorado. Figure 65 shows an idealized cross section of the Amethyst system. The authors believe that Coso Joint Venture holes 31-8 and 15-8 are in spreading fracture type reservoir conditions as are Department of Water and Power (DWP) Wells 43-7 and 88-1. Well 66-6 of DWP should be in or very close to a potential breccia pipe, but ongoing drilling still appears to be in an adjacent spreading fracture network. This well has demonstrated one important factor; open fractures go deep at Coso, with drilling encountering a significant entry of geothermal fluids at roughly 5,700 feet.

Although the spreading fracture network provides the bulk of the reservoir volume at Coso, the productivity of these fracture network zones is quite low compared to major brecciation zones and pipes. However, these zones can still be quite capable of commercial production. The spreading fracture networks are very susceptible to the effects of the various pluvial periods and will have both extensive vertical and horizontal temperature variations.

TEMPERATURE CONSIDERATIONS

The Coso geothermal field is made up of a magma at modest depth with a probable temperature of approximately 700 °C, cupolas of magma at 650 to 700 °C, vertical breccia pipes rising above the cupolas, and major mid-level fractures with temperatures of 200 to 300 °C. Surrounding the cupolas is a network of fractures with highly varying temperatures. Figure 66 shows an idealized isometric view of this circumstance. The vertical pipes should have largely maintained their temperature throughout pluvial times because of their tremendous vertical continuity. Thus, in pluvial times the temperatures in the spreading fracture network would be depressed by lateral flushing. Then during interpluvial times such as now, the temperature irregularly rises and spreads again. The outward pluming from the tops of individual pipes should, in addition, give localized hot zones in the fracture network downstream from the pipes.

Of great concern in planning drilling depths in the spreading fracture system is the estimation of probable maximum depth of flushing out by pluvial action. Figure 67 shows an idealized cross section of the Sierra Nevada, Rose Valley, the Coso resource area, and Panamint Valley. The given depth to bedrock in Rose Valley is slightly over 4,000 feet (the National Uranium Resource Evaluation (NURE) drill hole near Dunmovin was still in sand and gravel at 4,000 feet). Thus, it is highly unlikely that rapid lateral movement of a cold water mass eastward through the resource area would involve a mass more than slightly over 4,000 feet in vertical extent. On this basis, drill holes in the spreading fracture net should be targeted for a minimum of 5,000 feet (we are assuming an average of 1,000 feet of reheating since the last pluvial). Such holes will encounter varying degrees of reheating as the upper "temperature surface" is envisioned as being very irregular. Such holes will also encounter strong temperature reversals caused by pluming from the tops of the breccia pipes and related brecciated conduits of high permeability, as well as from complex interfingering between cold fluids still flowing easterly and hot fluids rising convectively (Figure 68) (Reference 43). Figure 69, based on actual data from Well NWC-1, a slim hole, shows a zone that appears undisturbed in terms of pluvial or flushing effects, and shows the depth at which molten rock can be expected in an underlying dike, cupola or apophysis.

RESERVOIR ESTIMATION

There are two readily available estimates of the energy potential of the commercially developable portion of the Coso geothermal system reservoir. One of these is the estimate prepared by Austin at the inception of serious geothermal exploration at Coso. This estimate was based on estimates of the area of the developable resource, the depth of producible reservoir, and the resource area's porosity and temperature. These factors were combined to yield a heat content of the rock and to gauge the probability of a viable fluid transport system to move the heat to where it would be useful. This series of estimates was 'ntegrated to yield a prediction of 1,000 megawatts for the total field with a life expectancy at this productive rate of about 1,000 years.

The Department of the Interior, in its voluminous Environmental Impact Statement (EIS) on the Coso lease program, published an estimate of 600 megawatts (Reference 44) for the field but did not specify any lifetime in terms of years. Estimates as high as 4,000 and 4,600 megawatts for Coso have been credited to unpublished studies conducted reportedly by investigators at Stanford Research and California Institute of Technology, respectively.

Now that there has been some successful drilling and the major structural components of the reservoir have been identified, it is a useful exercise to re-estimate what may be present. During this process we should establish clearly and unequivocally what is not present. Coso has no single pervasive horizontal reservoir. Reasonable estimates derived from calculations based on such a supposition will be fortuitous. Furthermore, although Coso has been drilled enough to enable an estimation of the kinds of productive zones present, only the crudest estimation is possible at this time with respect to magnitude of sustainable production possible.

The breccia pipes will be the eye-catchers of this resource area, because an active breccia pipe indicates that the complex heating and cooling patterns of the Amethyst Vein-type structures are not involved. The large pipe, the Condy Pipe, has a surface exposure of approximately 0.3 square mile. Assuming modest outward belling, the main pipe conduit is expected to have a cross section of approximately 0.2 square mile, be at least 5,000 feet in vertical extent, and be filled with breccia that is fairly open, easily averaging 10% open space.

The Condy Pipe is interesting in that it has a 300-foot steam cap just under the cap rock at the present time.

The ideal way to produce the Condy Pipe would be to drill clusters of wells to service several power plants, grouped about the well cluster. (Present regulations on power plant spacing are not consistent with the geologic realities of this type of resource (Reference 45).) The close clustering of power plants adjacent to individual pipes is desirable because of the tremendous lateral and vertical permeability within a pipe. Given an adequate series of well clusters, or simply enough wells, the steam cap should be able to expand vertically. Once an adequate steam cap, formed to maximize the well efficiency, is in place, production should be stabilized so that recharge into the lower portion of the pipe is sufficient to maintain a constant steam cap depth and pressure.

It is exciting to note that Well 75B-7 and the 75-7 and 75A-7 pair do not interact significantly at a 5-megawatt production rate despite being only 165 feet apart. This might lead one to reason as follows:

$$\begin{aligned}\text{Area of main pipe body} &= 0.2 \text{ sq. mile}\\ &= 5{,}600{,}000 \text{ sq. feet}\end{aligned}$$

$$\begin{aligned}\text{Area needed per 5-megawatt well} &= 200 \text{ feet} \times 200 \text{ feet}\\ &= 40{,}000 \text{ sq. feet}\end{aligned}$$

$$\begin{aligned}\text{Possible number of wells per pipe} &= 5{,}600{,}000 \div 40{,}000\\ &= 140 \text{ wells}\end{aligned}$$

$$\begin{aligned}\text{Probable power for Condy Pipe} &= 140 \text{ wells} \times 5 \text{ megawatts per well}\\ &= 700 \text{ megawatts}\end{aligned}$$

The remaining question is whether or not this is a reasonable rate of vertical flow. Since the pipe has a cross-sectional area of 0.2 square mile (if fully brecciated and involved) and hence an open transmission area of 0.2 square mile × 10% or 0.02 square mile, the open conduit area would be 560,000 square feet. If we then assume that a megawatt requires 40,000 lb/hr of steam (conservative) or 5,000 gallons per hour of water, then the total anticipated vertical flow of water would be 58,000 gallons per minute (gpm) for 700 megawatts or 7,400 cubic feet per minute. This equates to a vertical flow velocity of 0.2 in/min within the pipe, ignoring channeling and similar influences. With the differential pressures one can expect given steam cap growth, these do not seem to be geologically unreasonable numbers. Even if a steam cap is never found that can be exploited, we may still get twice the flow or 0.4 in/min. The probability that these differential pressures will be achieved in the Condy Pipe will, of course, depend on the rate of recharge into the lower portion of the breccia pipe.

To estimate the total recharge area, assume that the lower 1,000 feet of this pipe is collecting from splayed out fractures (as seen in many mineralized pipes that have been deeply mined for their residual metal content). The wetted collecting area is the bottom cross section of 0.2 square mile. The wetted recharge perimeter area is 0.2 mile (vertical) × 1.6 miles (circumferential) for a total wetted wall area of 0.3 square mile. This yields a total wetted recharge area of 0.5 square mile when the bottom is included. Recharge into the deep pipe will clearly be the controlling factor on production, not the near-surface phenomena of shallow wells or vertical flow rates within the pipe. Because of this recharge, return of spent fluids deep into the pipes will be an attractive method of maintaining the maximum in heat transfer capability, but must be done with an eye to controlling the buildup of noncondensable gasses in the steam cap. Thus, to maintain pipe production it is best to introduce liquid into the pipes, but not noncondensables. Noncondensables should not be allowed to accumulate in the production areas, especially in steam caps. Hense, noncondensables should be injected into colder, nonproductive Amethyst Vein-type structures where they will be diluted and swept out eastward and not allowed to accumulate.

In the case of the Jim Moore Pipe, we can make a similar set of calculations. The surface area of this pipe appears to be 0.1 square mile. Allowing for some modest degree of upward flaring or belling, it is reasonable to assume a pipe area of 0.06 square mile for the main conducting portion of the pipe. Wells 71-7 and 71A-7 in this pipe do not appear to significantly interact at a production rate of 3 megawatts each, with the distance between them comparable to the distance between two of the wells on the 75 pad. Wells 71-7 and 71A-7 were initially much more productive, but after being lined to control breccia fragment movemen. into the well bore, the performance has been significantly lowered. In the case of the Jim Moore Pipe we reason as follows:

Area of main pipe body = 0.06 sq. mile
= 1,700,000 sq. feet

Area per 3-megawatt well = 200 feet × 200 feet
= 40,000 sq. feet

Possible number of wells per pipe = 1,700,000 ÷ 40,000
= 43 wells

Probable power for Jim Moore Pipe = 43 × 3 megawatts per well
= 129 megawatts

In the Jim Moore Pipe there is a probable cross-sectional area of 0.06 square mile (if fully brecciated and involved). Thus, there is an open transmission area of 0.06 square mile × 10% = 0.006 square mile or 170,000 square feet. If we then assume, as we did with the Condy Pipe, that a megawatt requires 40,000 lb/hr of steam, then the anticipated vertical water flow rate in the Jim Moore Pipe would be 11,000 gpm or 1,400 cubic feet per minute. This calculates to 0.01 inch per minute as the vertical flow rate, again, not an unreasonable number. In both of these sets of calculations the authors are not trying for precise numbers. Thus, they have not gone into extensive calculations involving production of steam versus water in the event that the pipes are allowed to boil deeply, with resulting superheat, etc.

In the case of the Jim Moore Pipe, the wetted recharge area is estimated as follows: the wetted recharge perimeter area is 0.2 mile (vertical) × 0.9 mile (circumferential) for a total wetted wall area of 0.2 square mile. Add to this the cross-sectional area of 0.06 square mile for a total recharge area of approximately 0.3 square mile for this pipe. Once again, recharge into the deeper part of the pipe is expected to be the controlling factor.

The one notable difference with the Jim Moore Pipe is the lack of a well-developed steam cap. Whether this lack is because of a tighter seal or a greater internal pressure in the pipe is not known at this time. The lack of lateral permeability, especially in a pipe such as the Jim Moore that does not seem to be "pluming" outward or spilling outward externally, means that massive production from pipes should have little or no effect on adjacent or surface thermal manifestations based on Amethyst Vein-type structures or on the production from within such vein systems.

Lacking data on the extent of other types of breccia systems, for the sake of convenience we have simply assumed that all of the Navy contract lands, comprising 7 square miles that are roughly within the main producible area, consist of Amethyst Vein-type spreading fracture networks. Given good depth targeting, i.e., beyond 5,000 feet, the entire area is expected to be productive. Because of the widespread nature of these deeper fractures, which are expected to tighten with depth into a network of a few major fractures, we assume that the Navy lands can support one well on each 40 acres. To arrive at this estimate we are assuming that we would use a grid approach to drilling. In actuality we expect to sharpshoot along fractures at depth, and not to drill on a true grid. In any case, a reasonable estimate is 1 megawatt per well and one well per 40 acres. Thus we can expect 112 wells for a total of 112 dispersed megawatts throughout the Navy contract lands. Clearly, the target of greatest interest is to sharpshoot for more breccia pipes. This may well be a frustrating experience, as not all surface evidence will lead to pipe structures and not all pipes will be viable when drilled. At this stage of the development, breccia zones and, in particular, breccia pipes appear to be the key to large-scale success at Coso.

With respect to injection, it should be noted that introducing fluids into pipes will not be expected to support productivity in Amethyst Vein-type spreading fracture networks, nor will introducing fluids into the vein networks, such as into Well 31-8, support productivity in either the Condy Pipe or the Jim Moore Pipe. The separate nature of these two pipes is further indicated by the fact that the habit of the pyrite in each is markedly different; i.e., it is cubic in Jim Moore and pyritohedral in Condy, so that two distinct types of fluids appear to be present. The evidence from alteration and mineral deposition supports the interpretation that data from one pipe can be extrapolated only with great caution even to an adjacent pipe.

CONCLUSIONS

1. The Coso geothermal system, and in particular the land under contract by the Navy for development, comprises a composite reservoir consisting of four reservoir components whose locations appear to be controlled by radial fracture arrays. These arrays converge at four nodal points in or near the geothermal field, and are interpreted as marking cupola or apophysis locations at depth. The four components are:

a. Vertical breccia pipes with very large localized productive capacities

b. Fracture intersection breccia zones

c. Linear breccia zones

d. Spreading fracture networks

Drilling has verified two breccia zones, interpreted at this time as vertical breccia pipe systems, named the Condy Pipe and the Jim Moore Pipe.

2. The Condy Pipe, tested by four wells (two are actually an instrumented pair), appears capable of a maximum productivity of 700 megawatts, with the actual long-term sustainable productivity depending on deep recharge rates into the pipe.

3. The Jim Moore Pipe, tested by two wells, appears capable of a maximum productivity of 129 megawatts, with the actual long-term sustainable productivity depending on deep recharge in the pipe.

4. The Condy Pipe steam cap should be expanded in depth by production at the proper rates. Other pipes, such as the Jim Moore, that do not have a steam cap should be converted to steam cap systems by appropriate production rates.

5. Productivity from the Amethyst Vein-type spreading fracture networks at any given location will depend on the interplay of cold water flushing from the west, reheating from below, and leakage from the upper splayed part of individual breccia pipes. The estimate for this portion of the Navy-controlled reservoir, i.e., 7 square miles, is 112 megawatts.

6. The original Navy estimate for the overall productivity of the Coso geothermal field of 1,000 megawatts with a probable life of 1,000 years still appears to be a conservative but useful estimate. However, the Navy estimate of 350 to 450 megawatts for the Navy portion of the geothermal field will be low even if only one more major productive breccia pipe is found.

7. The Coso reservoir can not be modeled as a simple horizontal permeable zone. Rather, the reservoir is a complex interplay of four types of reservoir components involving a major vertical flow of hot fluids and an easterly flow of cold fluids that are actively mixing at this time through a vertical range of at least 4,000 feet.

8. Autobrecciation is seen as a major source of fracturing in the various reservoir components. Room for the fracturing is the result of the uplift of the central basement ridge beneath the dome field, combined with periodic subsidence that would occur when eruptive phases terminate periods of magma volume expansion. This expansion would result from the periodic vesiculation caused by water accumulation in the upper portions of the magma chamber.

9. Drilling into the Amethyst Vein-type spreading fracture network will be very risky from the standpoints of productivity and temperature for wells targeted to less than 5,000 feet. Scattered good production can be expected at depths of 1,500 to 2,000 feet, depending on local pipe leakage and reheating rates in individual fractures.

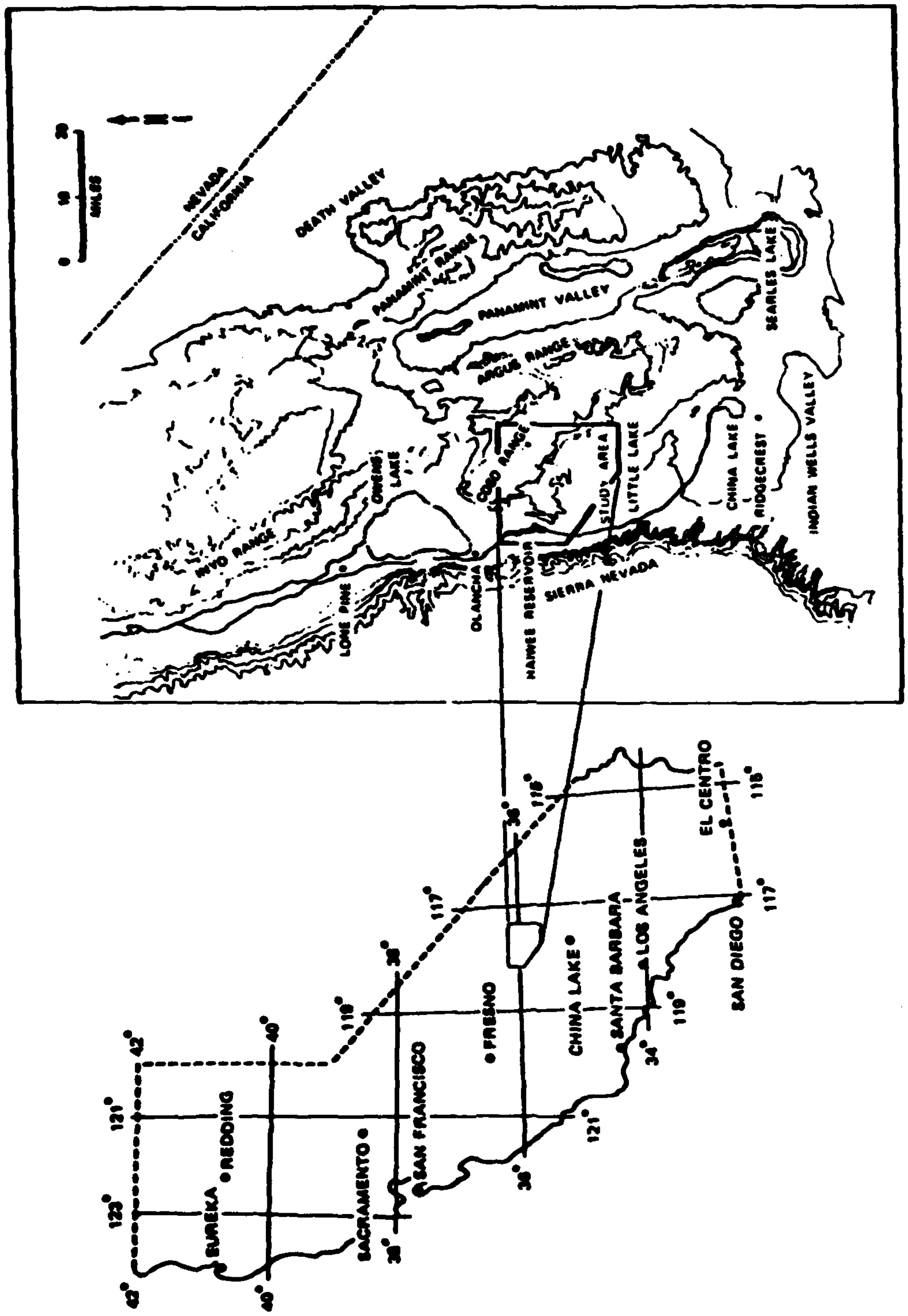


FIGURE 1. Location Map Showing the Coso Geothermal System in Relation to Major Cities in Southern California.

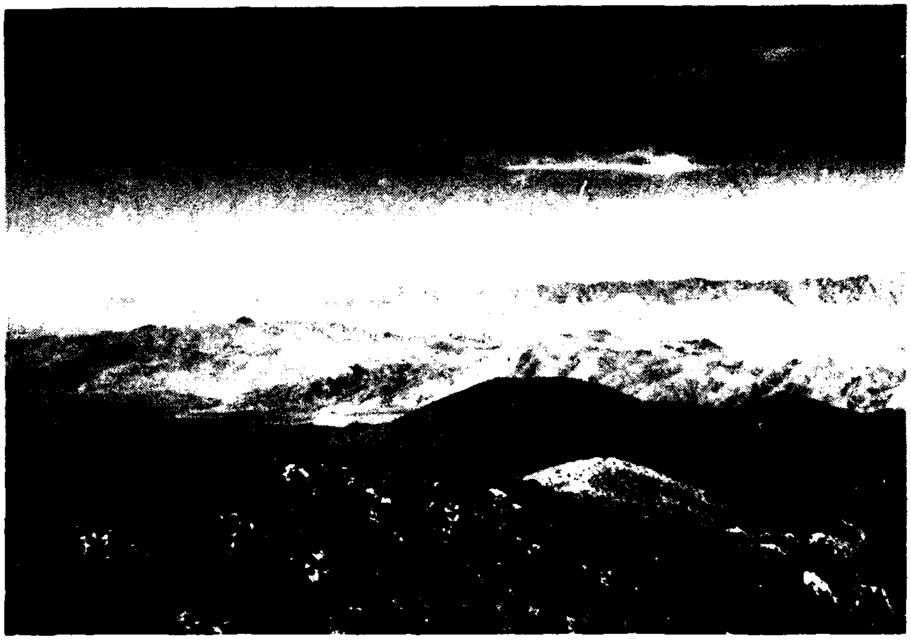


FIGURE 2. View of the Coso Dome Field From the Silver-Gold Prospect Area of Silver Peak, Looking Southwest (June 1985).

FIGURE 3. Remains of the Coso Hot Springs Resort Structure Called "The Bottling Works." Located along the "Hot Springs Fault" on the east side of the Coso perlite-dome field. Photograph taken 19 November 1948.

FIGURE 4. Small Mercury Mill of the Lynch Quicksilver Property That Serviced the Open-Pit and Underground Mine. Now known as the Nicol or Basin deposit.

FIGURE 5. Site of Pumice Mine Adjacent to the Naval Weapons Center Boundary North of Sugarloaf. Mine inactive in June 1985 when photographed.

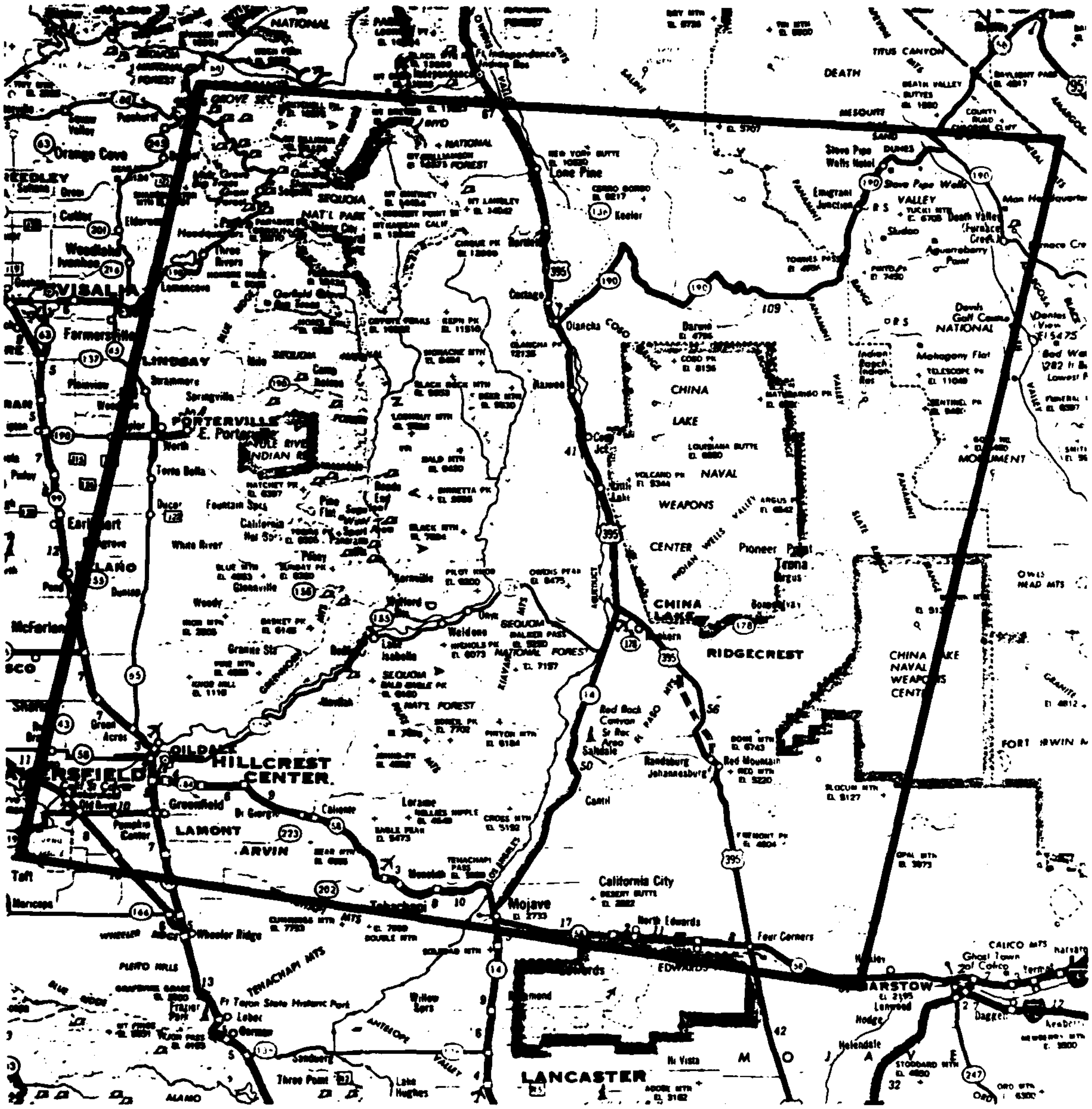


FIGURE 6. Location Map of Eastern Central California Showing the Area Covered by Satellite Photographs (Figures 7 and 8).

FIGURE 7. Unretouched Satellite Photograph of the Coso Geothermal Area.

FIGURE 8. Retouched Satellite Photograph of the Coso Geothermal Area With Major Geologic and Geographic Features and Arcuate Fracture Patterns Outlined.

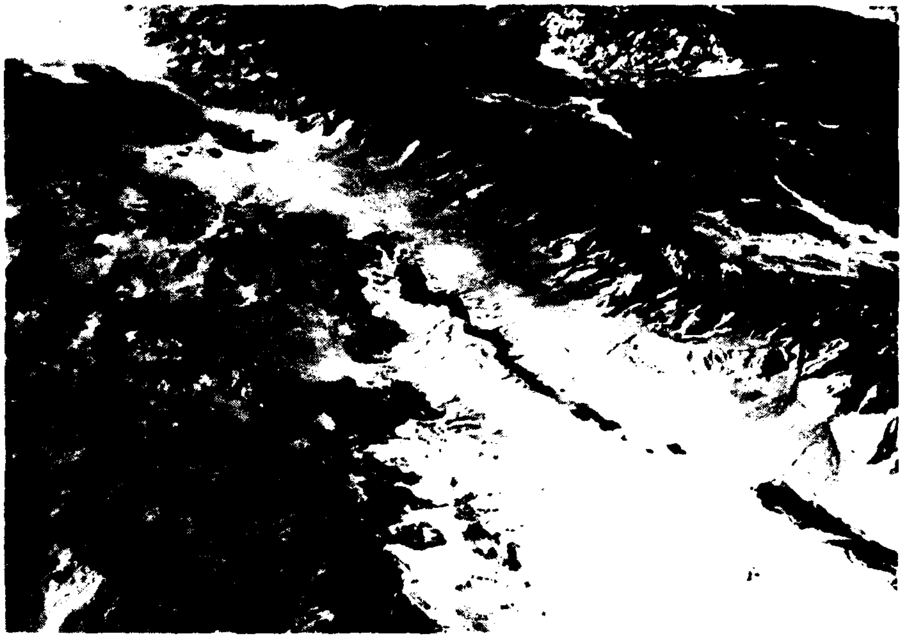


FIGURE 9. Unretouched High-Altitude Photograph Looking South Along the West Side of the Coso Geothermal System.

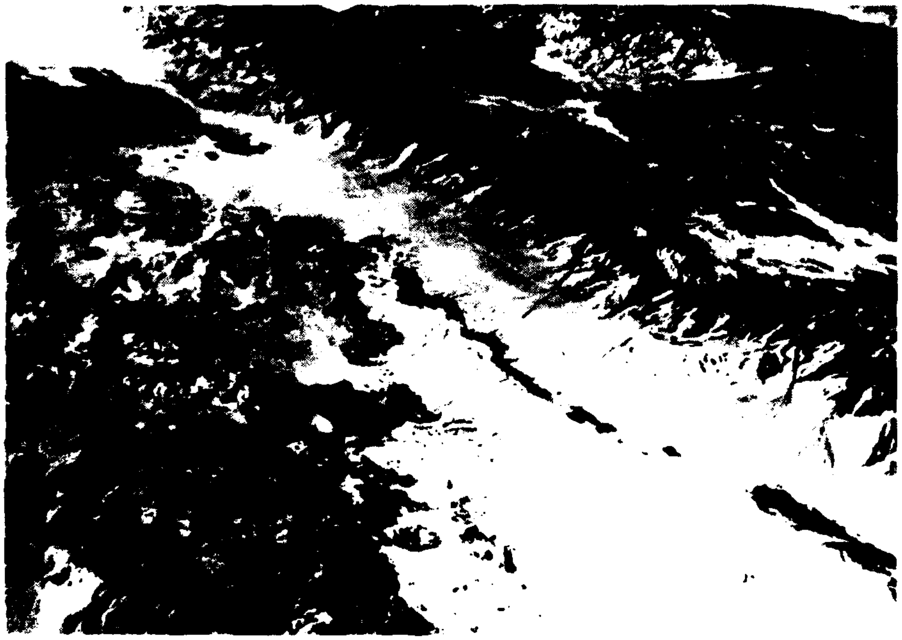


FIGURE 10. High-Altitude Photograph Looking South Along the West Side of the Coso Geothermal System With the Arcuate Fractures on the Sierran Side Outlined.

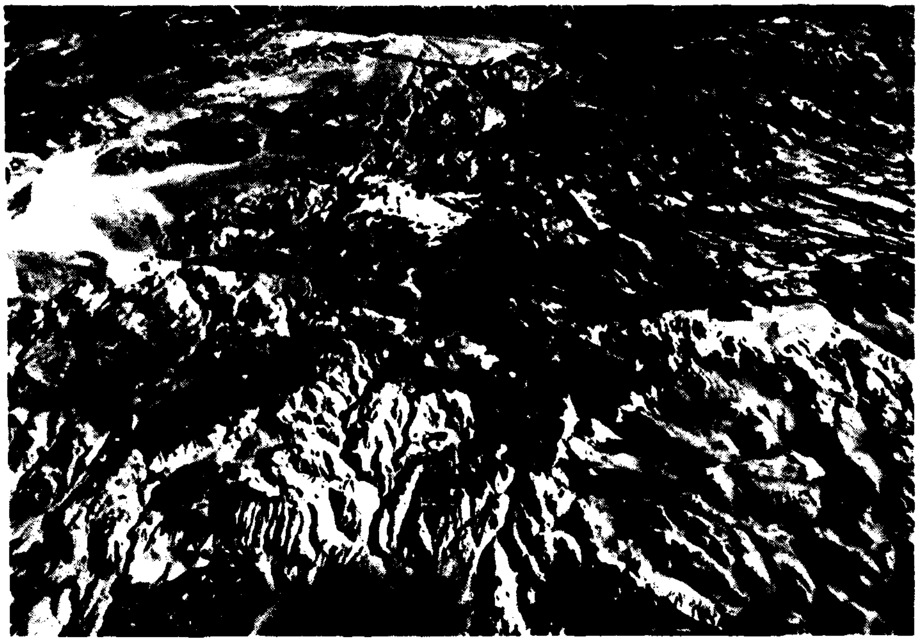


FIGURE 11. High-Altitude Photograph of the Northeastern Portion of the Circular Feature, Believed by the Authors To Represent the Surface Expressions of the Main Magma System at Coso.

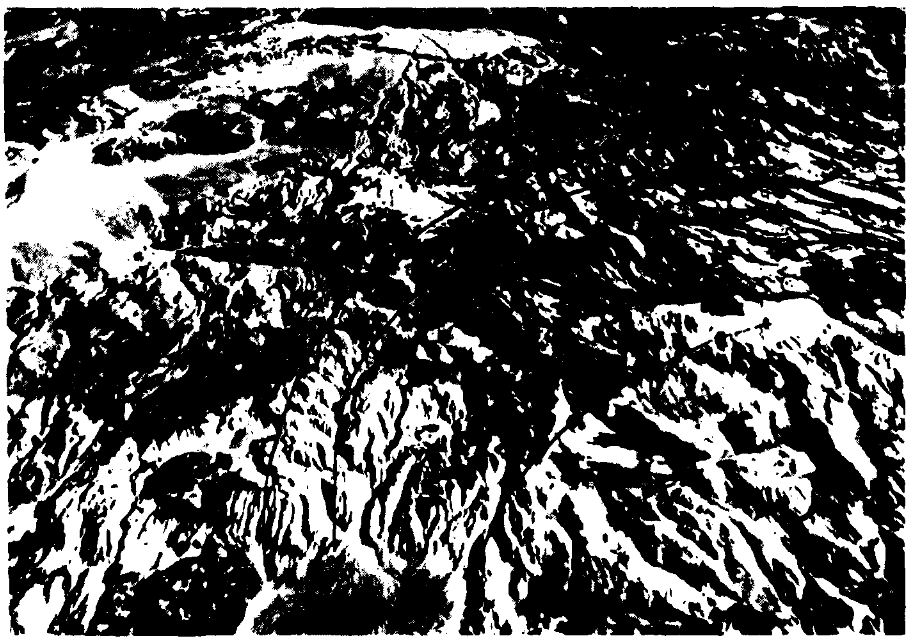


FIGURE 12. High-Altitude Photograph of the Northeastern Portion of the Coso Geothermal Area With Prominent Arcuate and Concentric Fractures Outlined.

FIGURE 13. An Unretouched Photograph of the Perlite Dome and Vent Complex Known as Glass Mountain or Sugarloaf.

FIGURE 14. Photograph of Figure 13 With Individual Vent and Dome Systems Outlined (Ignoring the Mechanics of Which System Overlaps Which).

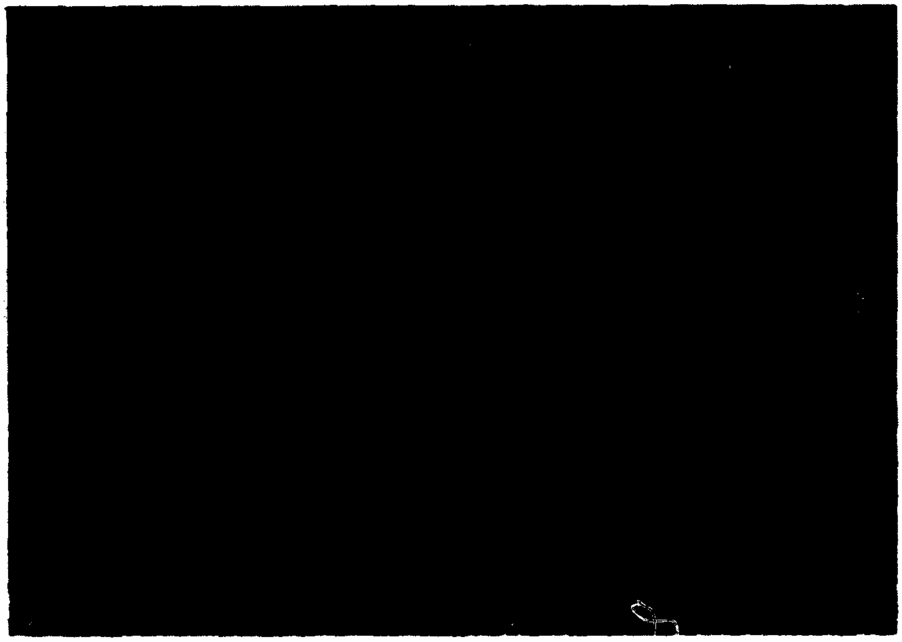


FIGURE 15. An Old Deeply Eroded Perlite Dome. Located north of the Coso resort area (the dome eruption dated at 1.04 million years by the USGS).

FIGURE 16. A Perlite Dome Complex at Coso. Extensive gullying and outwash of slope material is seen. The eruption was dated at 244,000 years (± 28,000 years) by the USGS. Compare this, however, with the subdued wreckage of a dome dated at 293,000 years (± 35,000 years) shown just north of Sugarloaf in Figure 13. (Reference 8.)

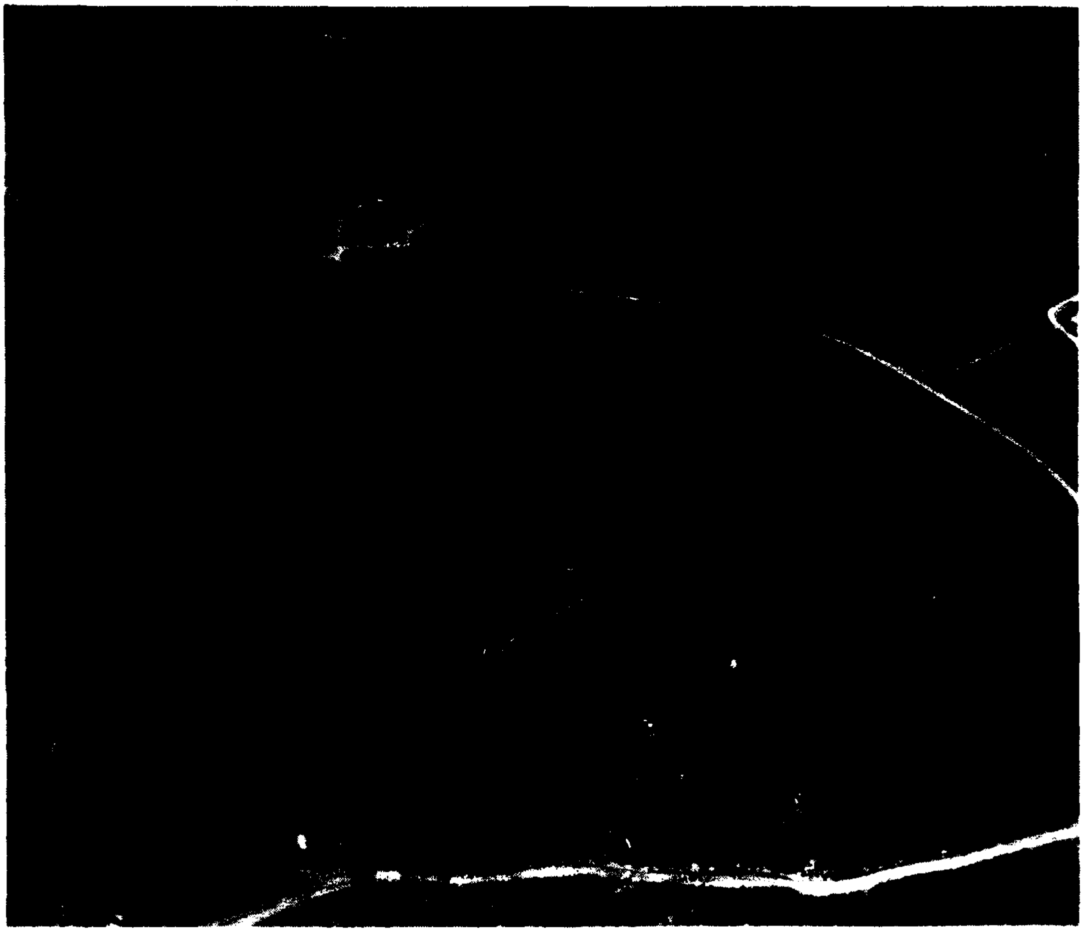


FIGURE 17. A Young Crisp Perlite Dome Dated at Less Than 100,000 Years (Reference 8) With Negligible Erosion Damage That Partly Fills an Explosion Ring. The original vent pit within the explosion ring has not yet filled with alluvium, features that are inconsistent with the reputed high rainfall periods of the last two pluvial periods. (Note DWP Well 66-6 in background.)

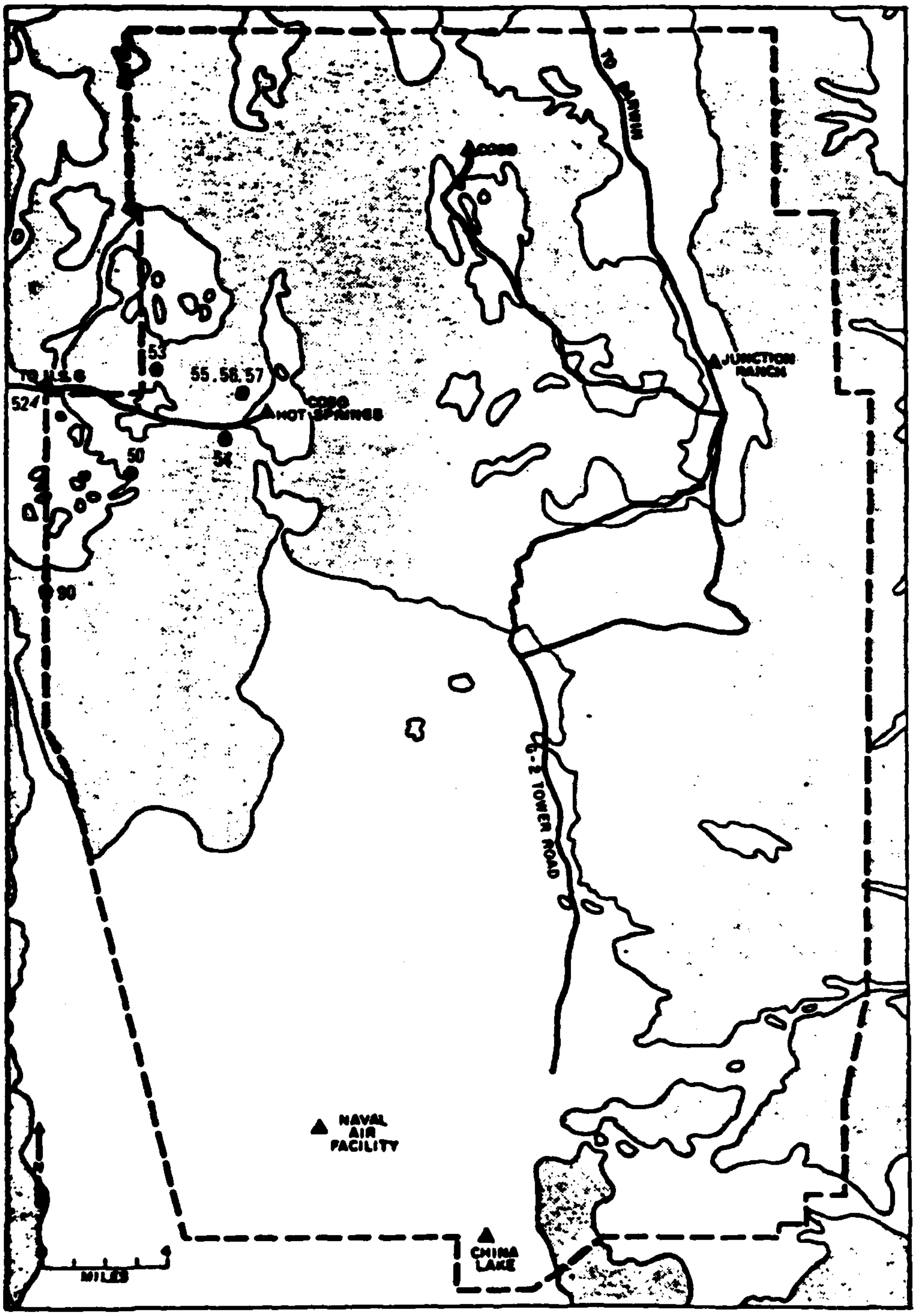
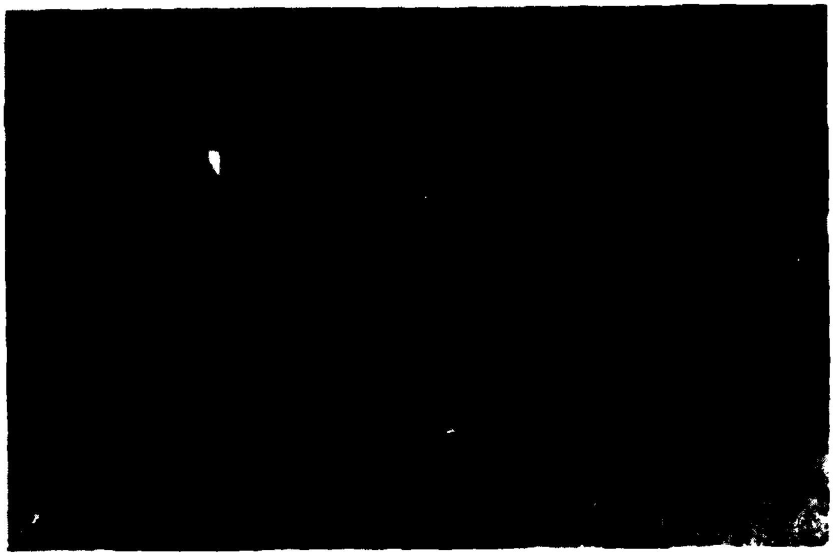


FIGURE 18. Location Map for Samples of Typical Basement Rocks of the Coso Geothermal System.

(a)

(b)

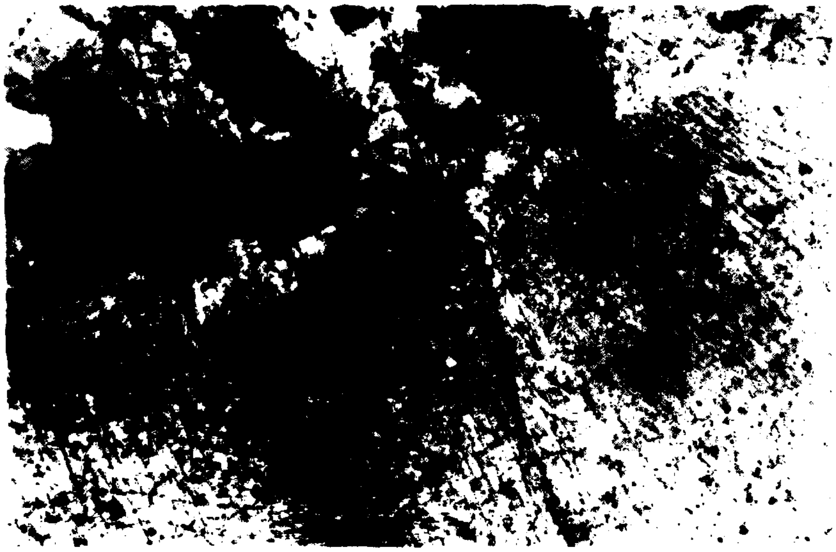
FIGURE 19. Photomicrographs of Two Diorite Samples From the Coso Geothermal Area. (a) Sample 56 under plane-polarized light. (b) Sample 56 under crossed nicols. (c) Sample 57 under plane-polarized light. (d) Sample 57 under crossed nicols. Note that in Sample 57, the crystals of plagioclase have labradorite cores and andesine rims. The crystals are mostly unaltered whereas Sample 56 has scattered alteration of the plagioclase due to hydrothermal or deuteric action.



(c)

(d)

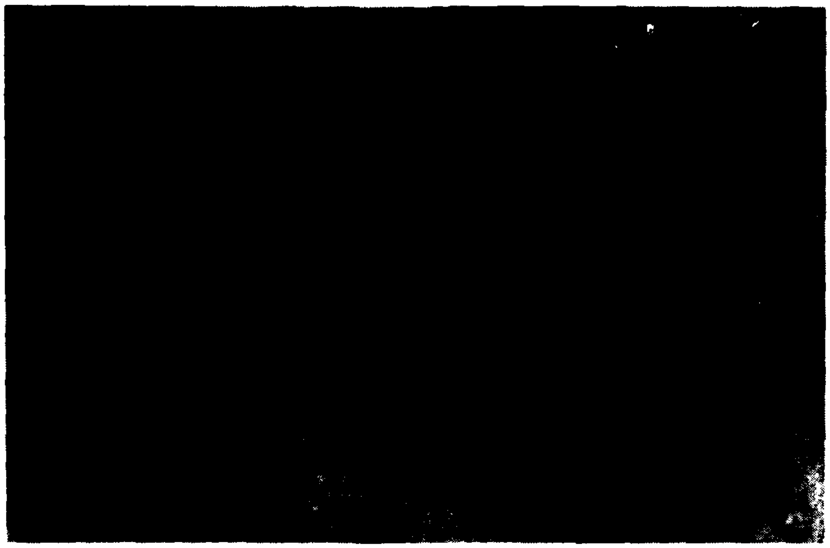
FIGURE 19. (Contd.)



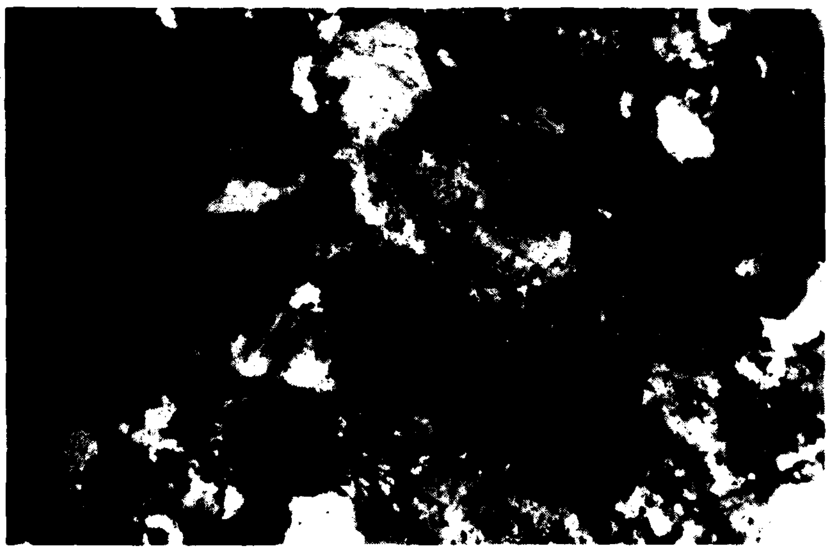
(a)

(b)

FIGURE 20. Photomicrographs of Fresh Granodiorite. (a) Sample 50 under plane-polarized light, seen to be a simple mixture of light and dark minerals; (b) same sample under crossed nicols, seen to be also a mixture of potash feldspar (cut by wavy lines), plagioclase feldspar (twinned), and quartz (clear, gray, and interstitial); and biotite and hornblende as dark minerals.

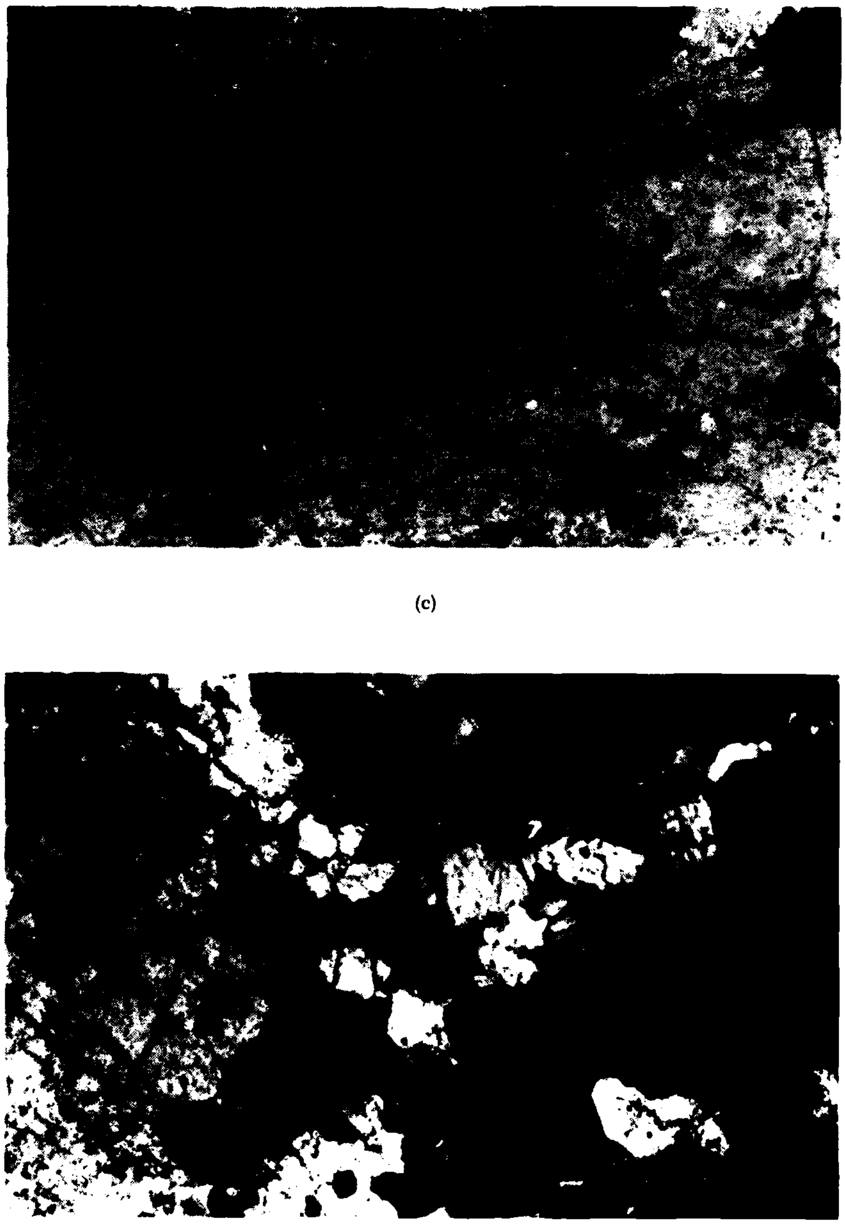


(a)



(b)

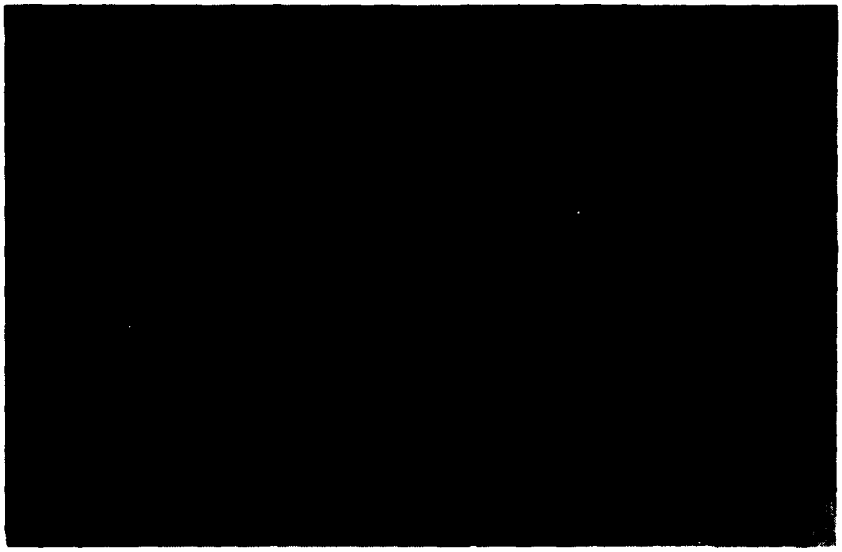
FIGURE 21. Photomicrographs of Granite From the Coso Geothermal Area. (a) Sample 52 shown in plane-polarized light, (b) Sample 52 under crossed nicols (was originally a medium-grained granite that is now a mass of quartz because of cataclastic and fluid action). Note formation of clay and sericite, and of iron oxides (forming caused by weathering). (c) Sample 55 shown in plane-polarized light, (d) Sample 55 shown under crossed nicols. This sample is a medium- to coarse-grained fresh rock, but has ragged grain boundaries and has been badly stressed as shown by bent crystals and fine-grained quartz indicative of cataclastic damage.



(c)

(d)

FIGURE 21. (Contd.)



(a)

(b)

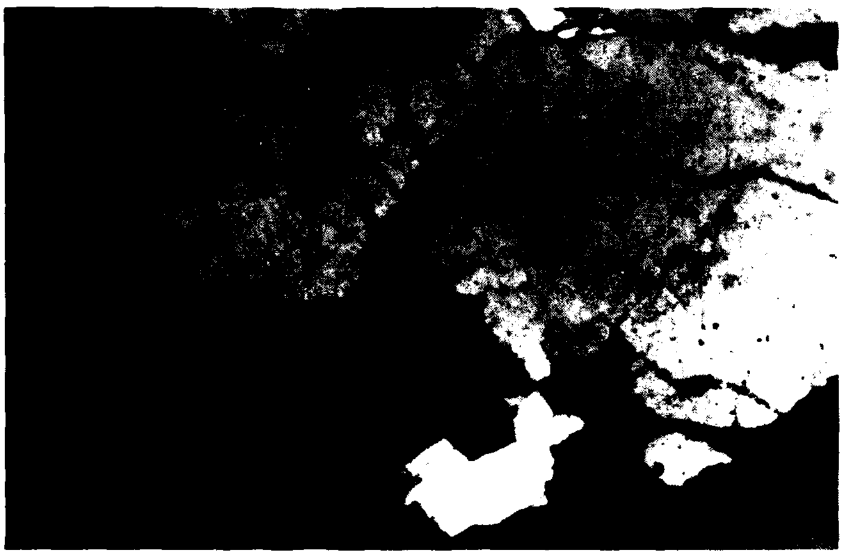
FIGURE 22. Photomicrographs of Leucogranite From the Coso Geothermal Area. (a) Sample 53 is coarse-grained, fresh, and shown in plane-polarized light; (b) Sample 53 is shown under crossed nicols; (c) Sample 54 is generally fresh with only slight weathering and occasional fine quartz on grain boundaries, shown in plane-polarized light; (d) Sample 54 is shown under crossed nicols; (e) Sample 90 is coarse-grained and fresh, shown in plane-polarized light; and (f) Sample 90 is shown under crossed nicols.

(c)

(d)

FIGURE 22. (Contd.)

(e)



(f)

FIGURE 22. (Contd.)

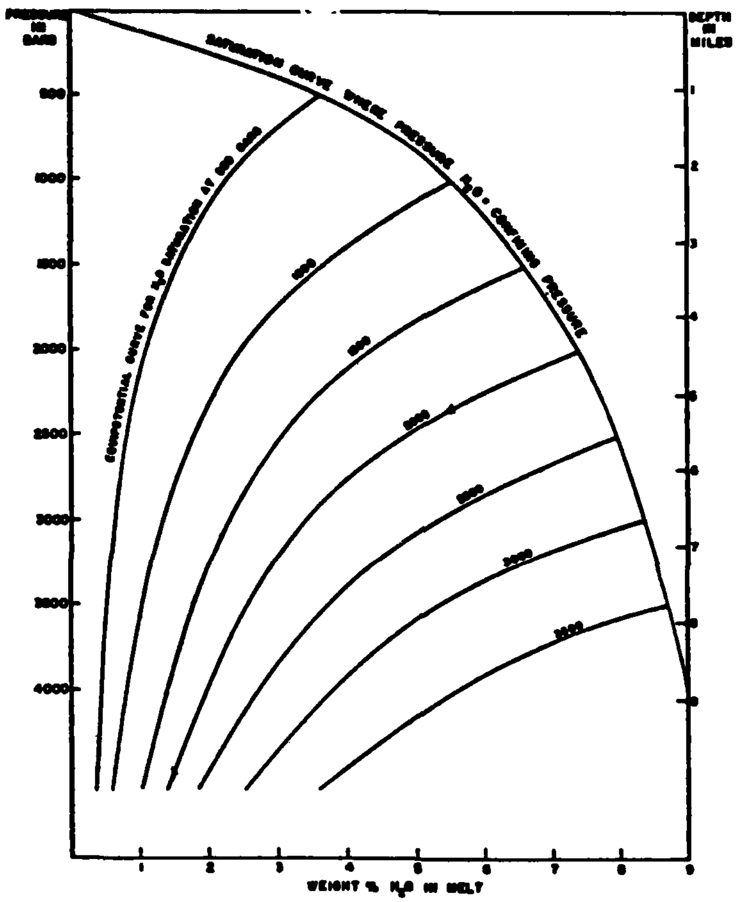


FIGURE 23. Distribution of Water in a Silicate Melt as Shown by Kennedy (Reference 16).

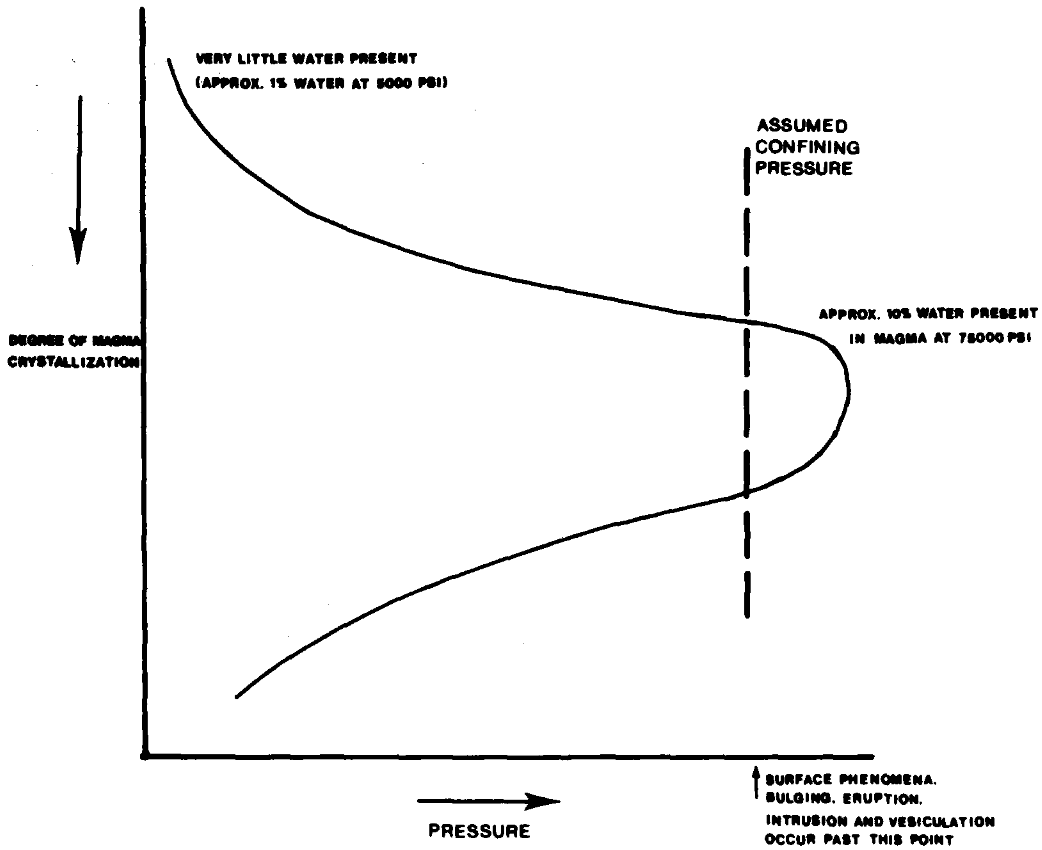


FIGURE 24. Idealized Residual-Liquid, Vapor-Pressure Diagram for Magma. The diagram shows the vesiculation time, volume expansion, and resulting injection of dikes; as well as possible vulcanism. Also indicated is extensive, increased upward migration of hot fluids and gasses. (Data is from Edwin Roedder, personal communication with Carl F. Austin, 1954.)

FIGURE 25. Satellite Photograph of the Coso Geothermal System Area. Shows the two major fractures within or adjacent to the area in which the Coso intrusive system has formed.

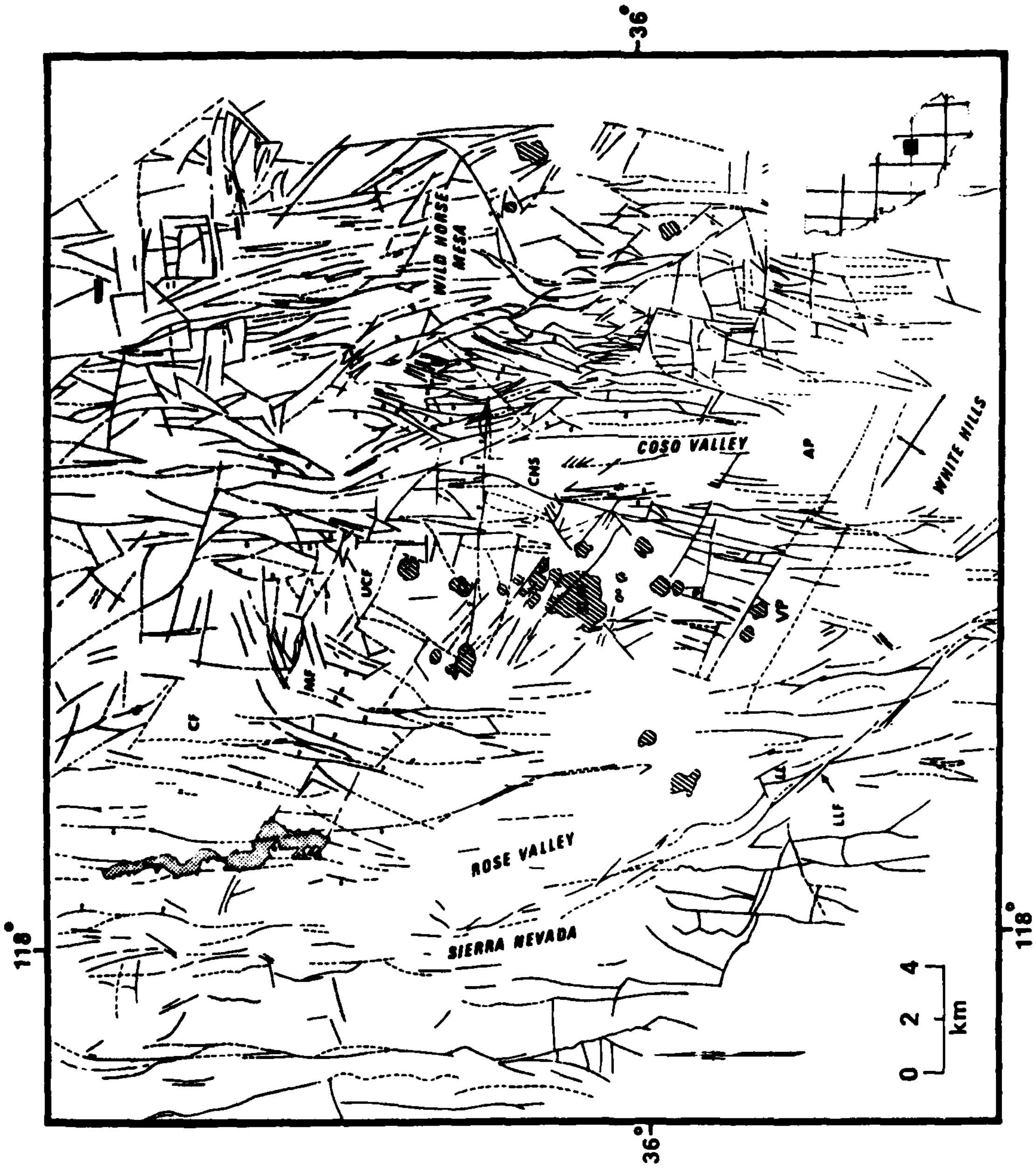


FIGURE 26. The Major Fracture Pattern of the Coso Geothermal System as Mapped by Roquemore (Reference 17).

FIGURE 27. Compressional Features of the Coso Geothermal System Region.

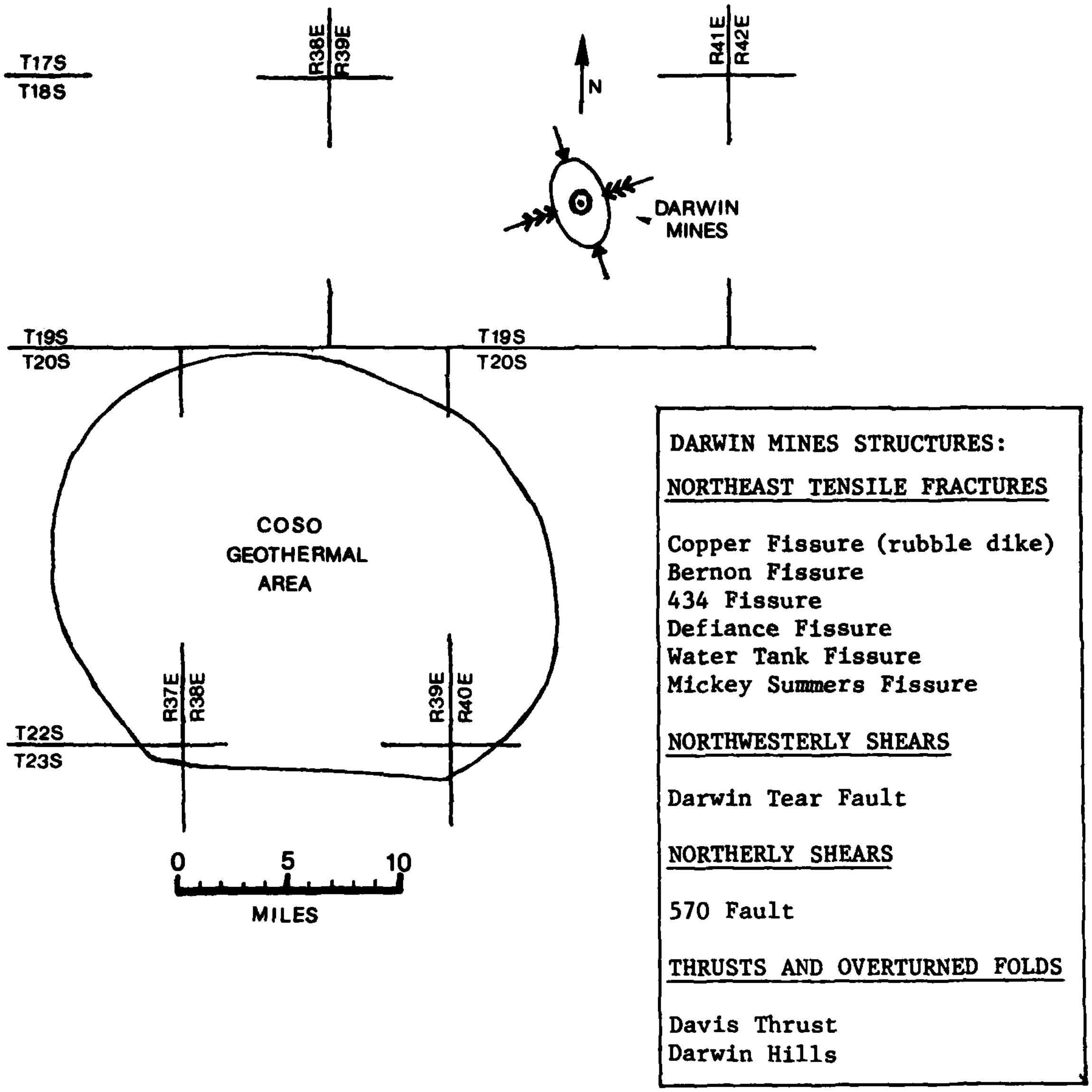


FIGURE 28. Strain Ellipsoid That Explains the Fracture Pattern of the Darwin Mines Shows Strong Compression in the Southwest to Northeast Direction. Extension is expressed by mineralized fissures trending northeast.

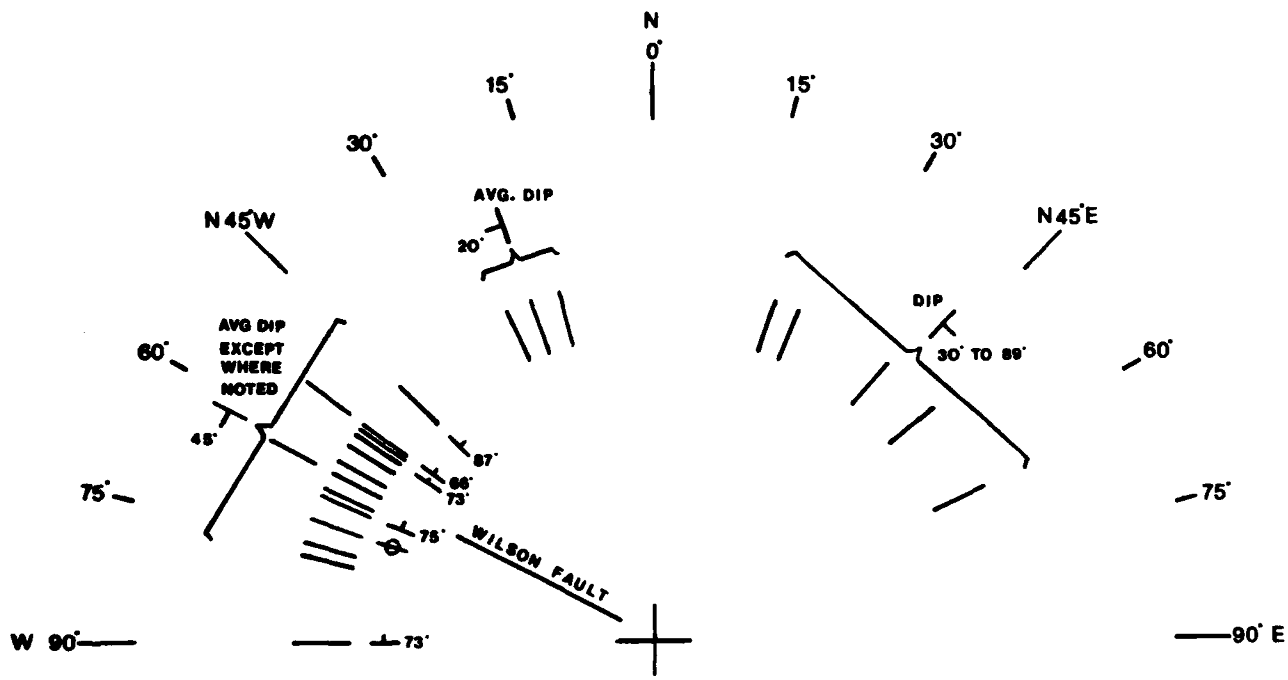


FIGURE 29. Orientation of the Various Types of Fracture-Controlled Mineral Deposits of the Naval Weapons Center in the Vicinity of the Wilson Fault Zone.

(a)

(b)

FIGURE 30. Former Coso Hot Springs Resort Area. (a) Main resort structure (photograph taken 19 November 1948, looking south), (b) dug hole at what is believed to be the former "mud spring" site south of the buildings.

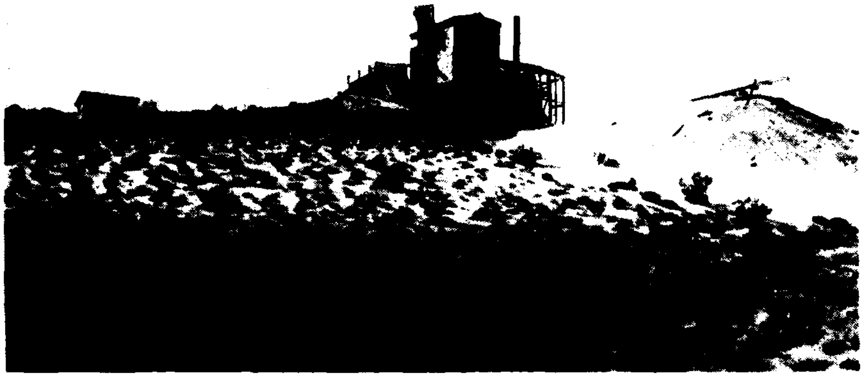


FIGURE 31. King Mill Adjacent to the Devils Kitchen Open-Pit Mercury Mine. The principal mercury mill of the area (photograph taken 19 November 1948).

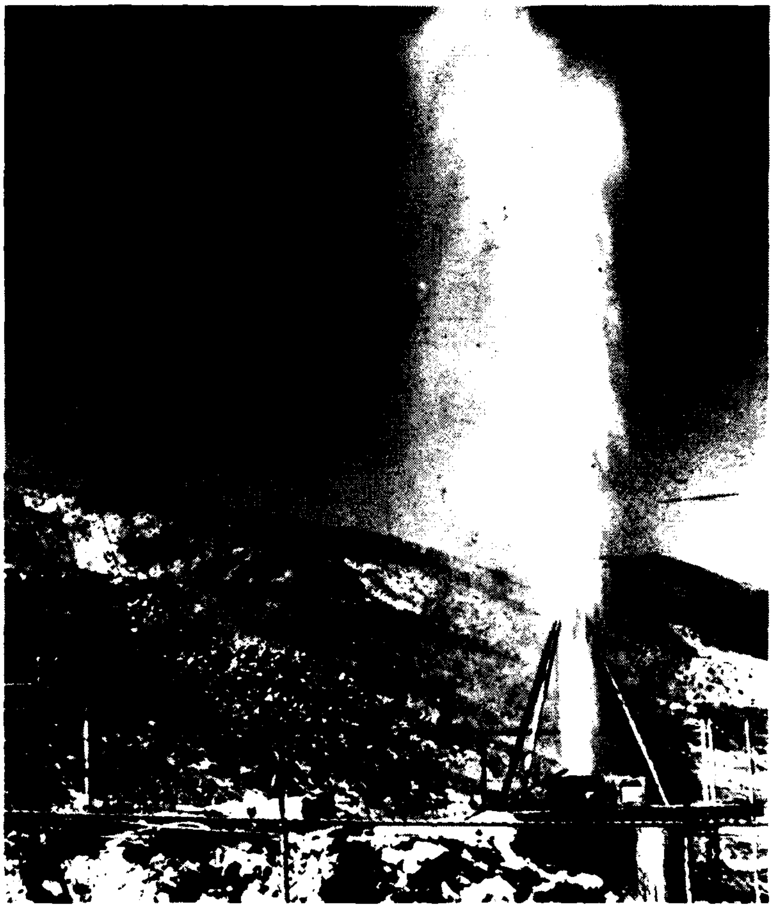


FIGURE 32. The Mid-1960s Era Navy Test Well Coso No. 1 on the "Hot Springs Fault," Opened and Flowing (375 Feet Deep, 289°F).

(a)

FIGURE 33. The Outflow End of Rose Valley. (a) Satellite view and (b) satellite view retouched to show (A) basalt-filled river channel and (B) landslides.

(b)

FIGURE 33 (Contd.)

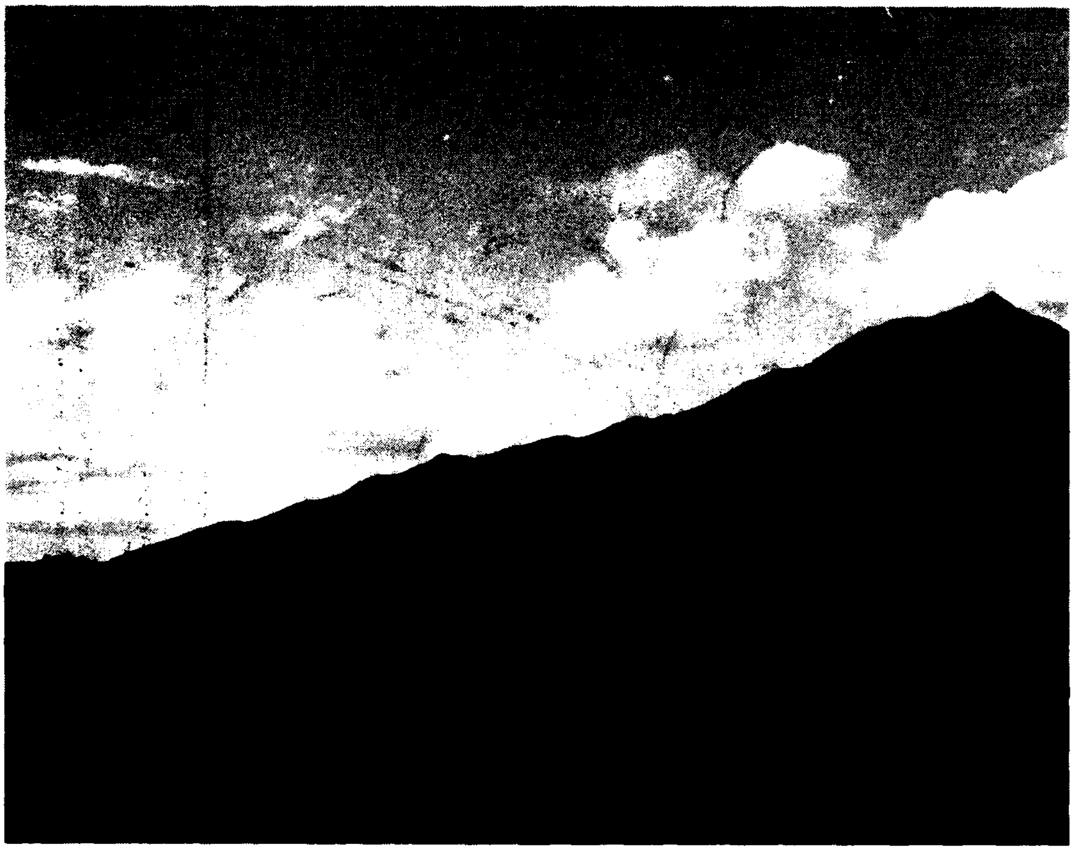


FIGURE 34. Side View of the Landslide Called Out in Figure 33b.

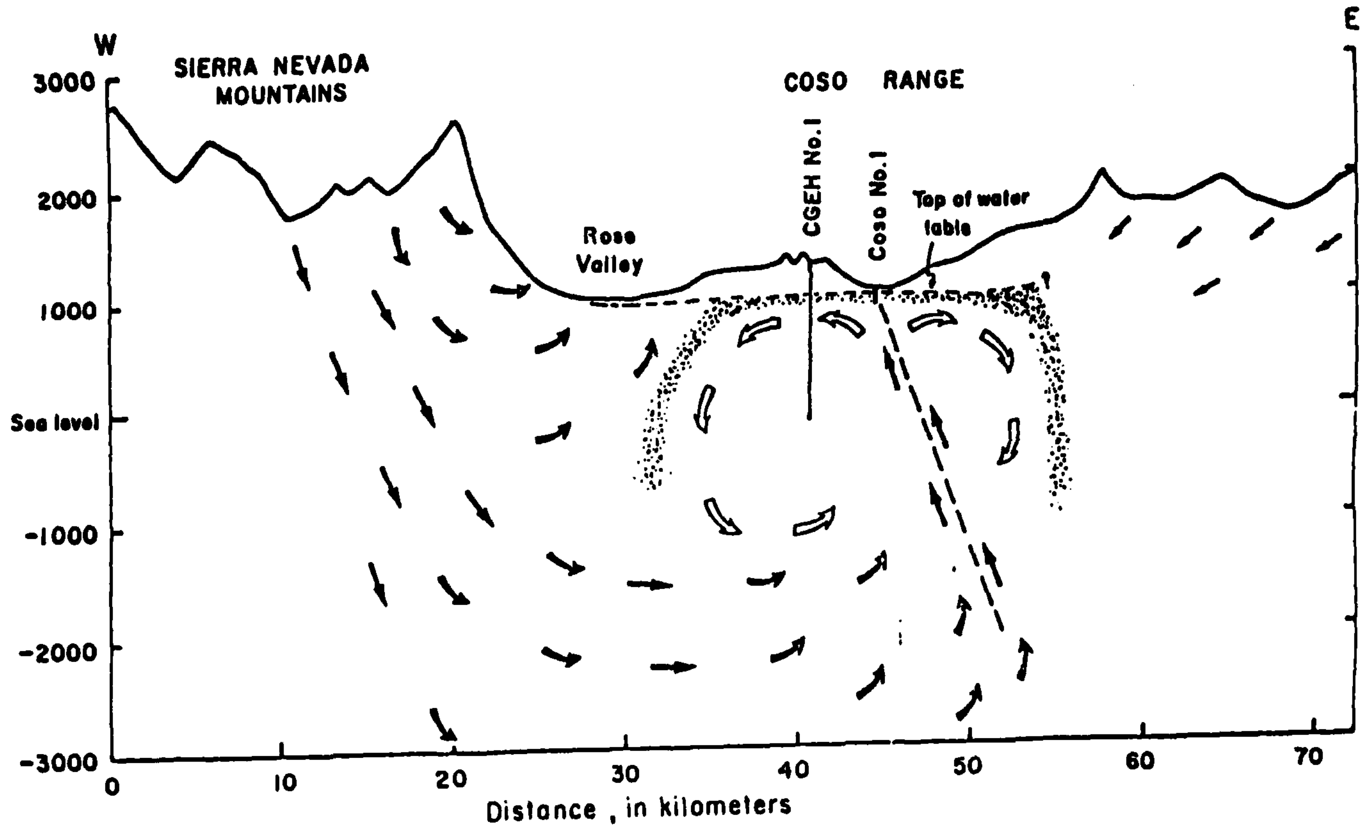


FIGURE 35. Schematic Cross Section of the Overall or Generic Flow Pattern of Fluids Into and Through the Coso Geothermal System (After Fournier and Thompson, Reference 32).

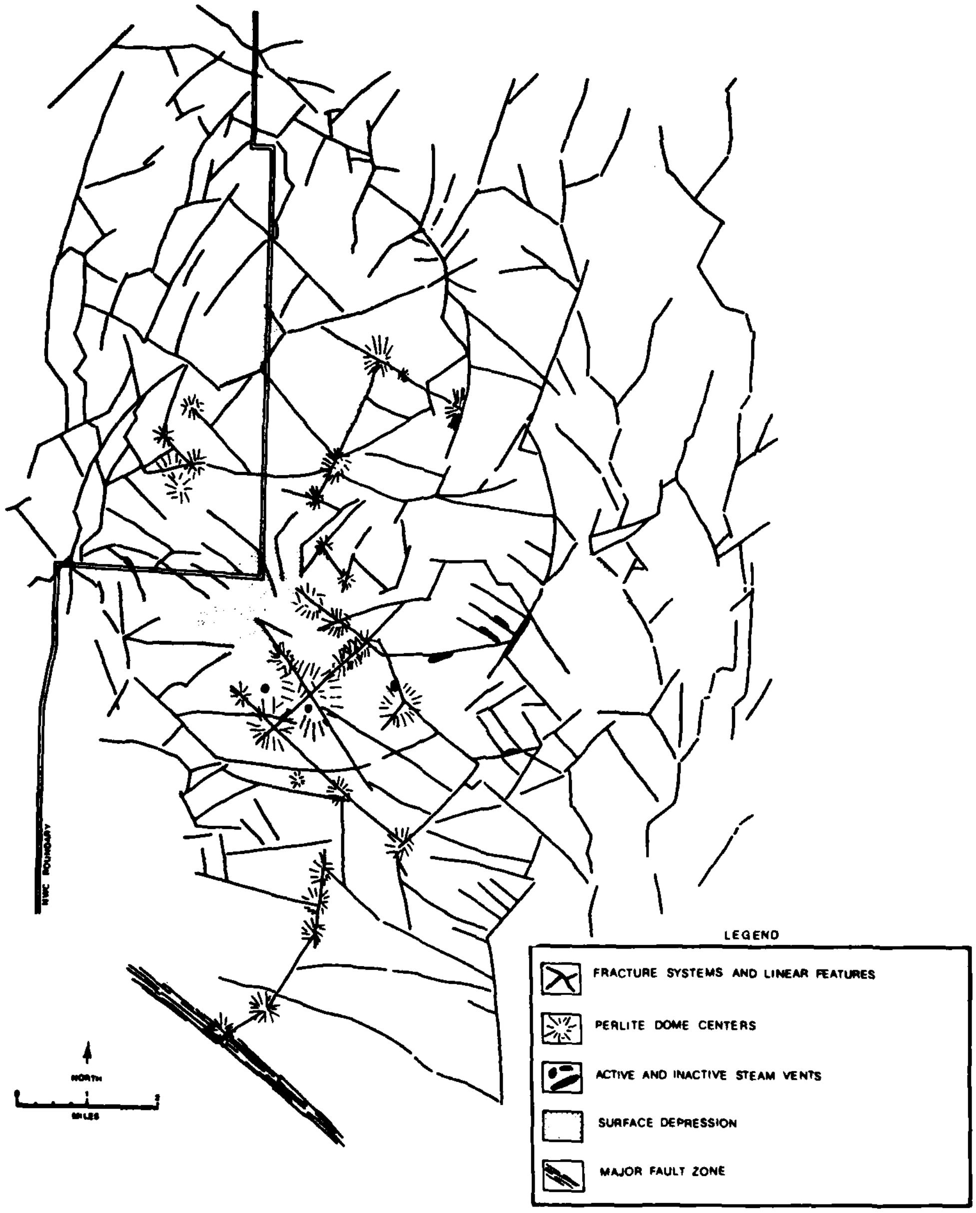


FIGURE 36. The Lineation Map of the Coso Geothermal System. Prepared by Austin in 1963 as the basis for exploration of the steam field hypothesized to be present.

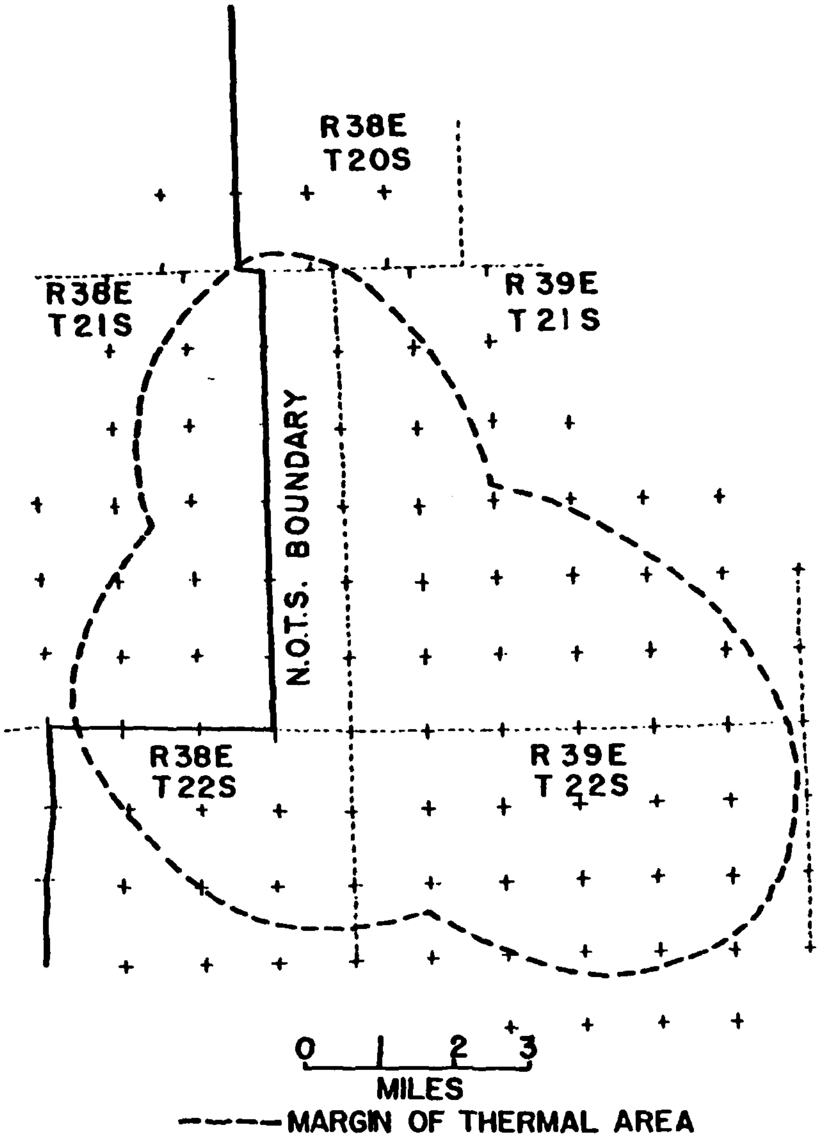


FIGURE 37. The Margin of the Potentially Valuable Portion of the Coso Geothermal Area. Identified in a 1964 publication (Reference 5).

FIGURE 38. Photogeology of the Coso Geothermal Area. Prepared by Ward Austin, 18 July 1971 (Reference 6).

FIGURE 39. Perlite Dome Field and Main Reservoir Portion of the Coso Geothermal Area.

FIGURE 40. The Apparent Perlite Domes and Dome Free Vents. Plotted on the photograph of Figure 43 without regard for skirt overlap, and the apparent fractures that controlled these features.

FIGURE 41. A Projection of the Fractures of Figure 40 Showing Them Converging at Four Nodes. *These are interpreted as cupola centers. The radial fractures are* interpreted as being due to hoop stresses caused by cupola vesiculation with resulting vulcanism.

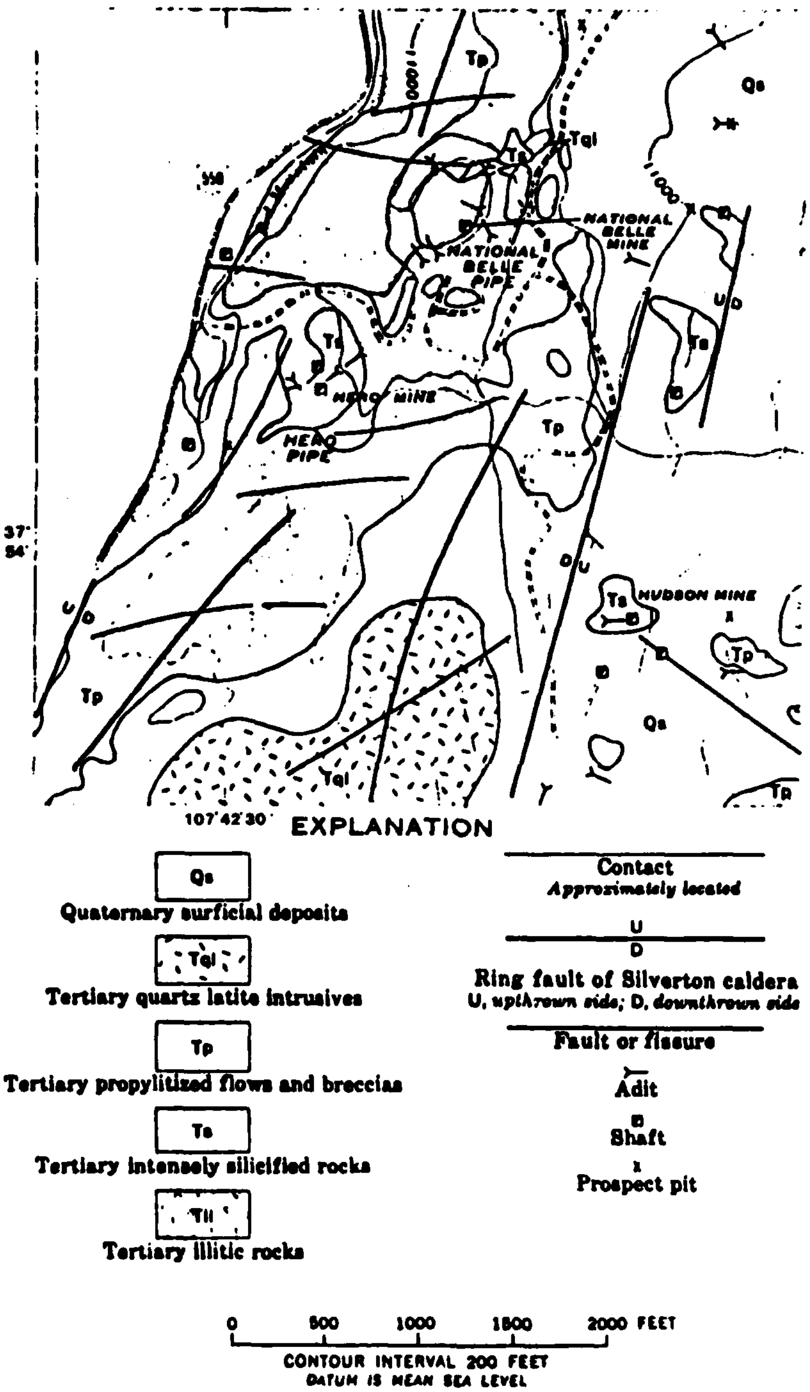


FIGURE 42. Map of a Portion of the Breccia Pipe Cluster of Red Mountain Pass, Colorado. (Modified from Fisher and Leedy, Reference 37.)

FIGURE 43. National Belle Pipe Outcrop at Red Mountain, Colorado. Taken from the outcrop of the adjacent pipe to the south.

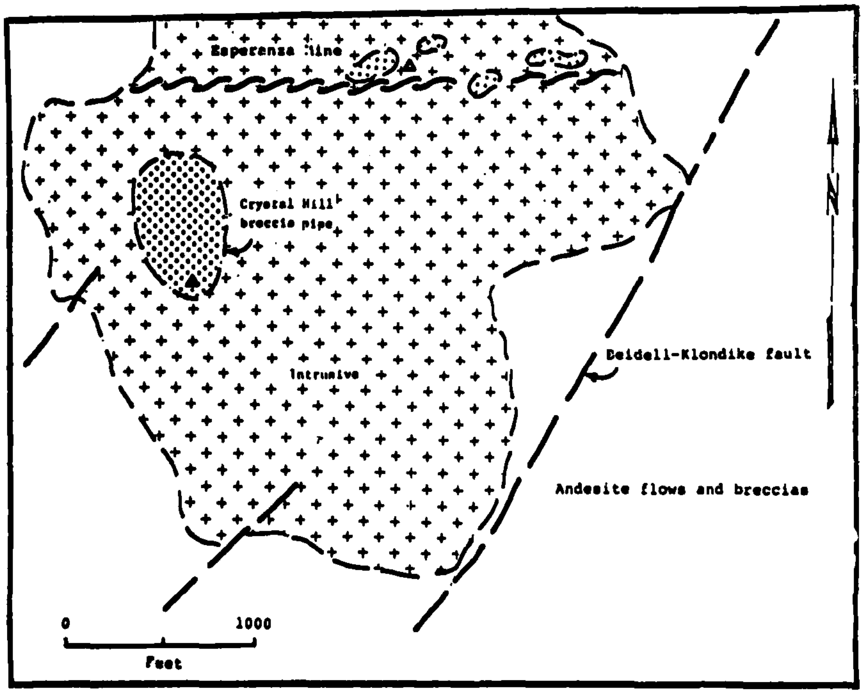


FIGURE 44. Map of the Crystal Hill, Colorado Area. Showing pipes known as of 1984 (Reference 38).

FIGURE 45. Crystal Hill Pipe. Note the sharp boundary of the pipe, marked by both color and texture change, with negligible permeability and mineralization outside of the pipe.

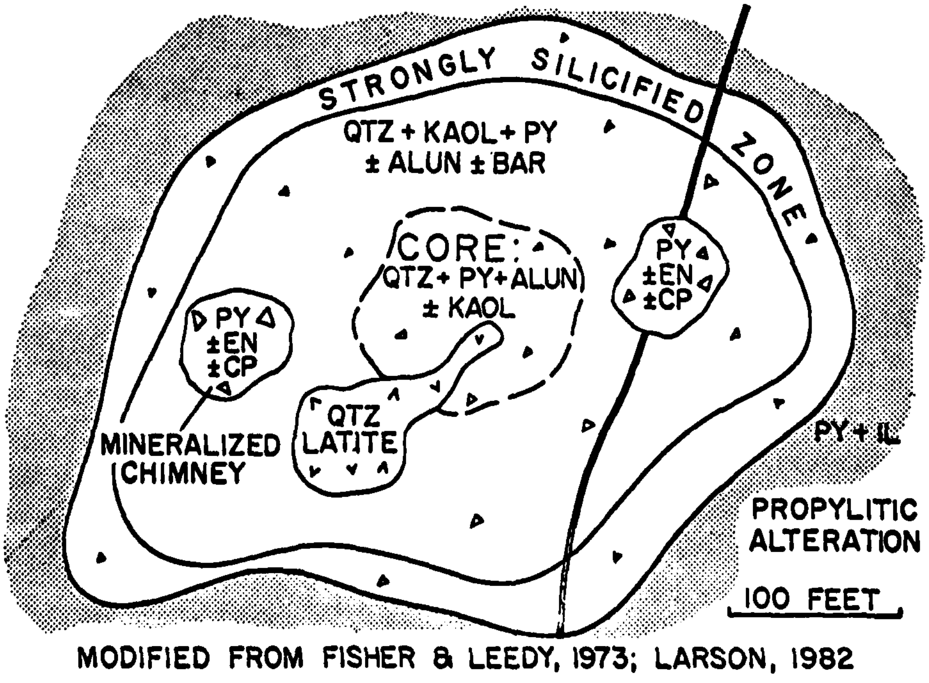


FIGURE 46. Adaptation of Idealized Plan View Through a Red Mountain Type of Pipe (Reference 39).

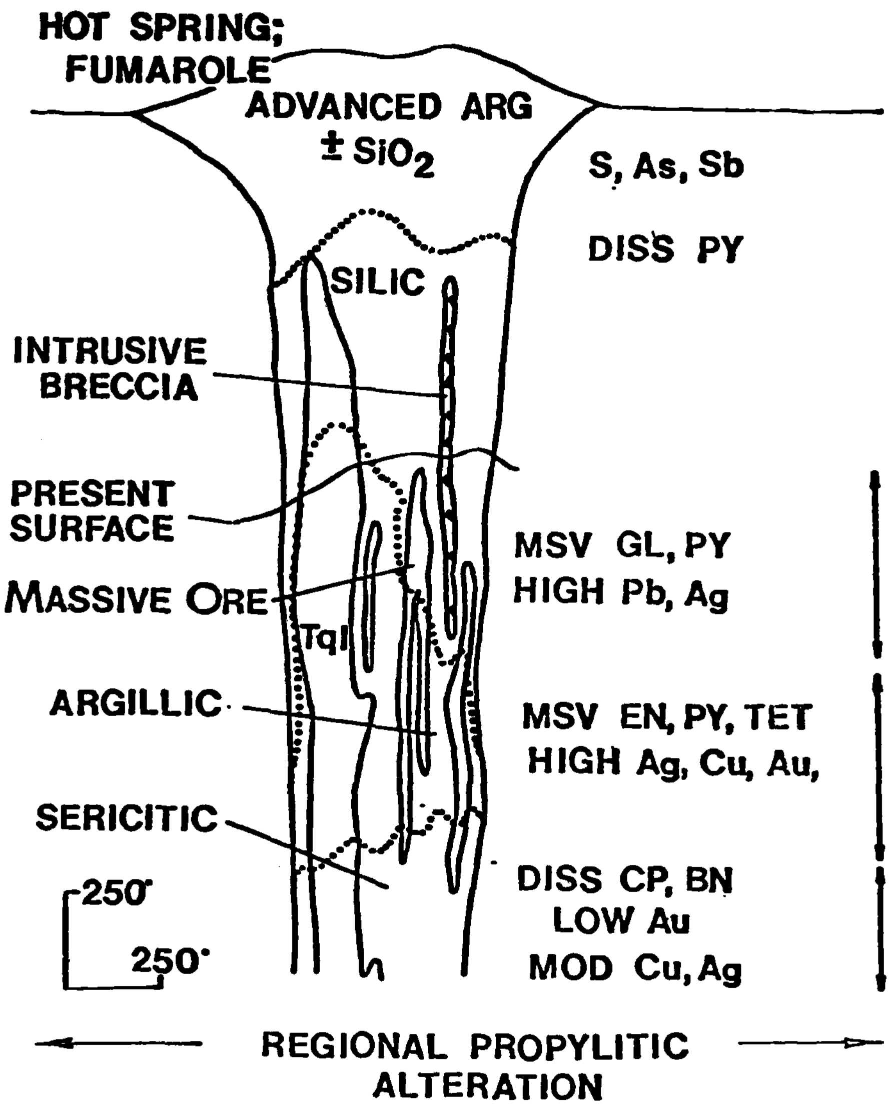


FIGURE 47. Idealized Cross Section Through a Red Mountain Type of Pipe, Adapted From Reference 39.

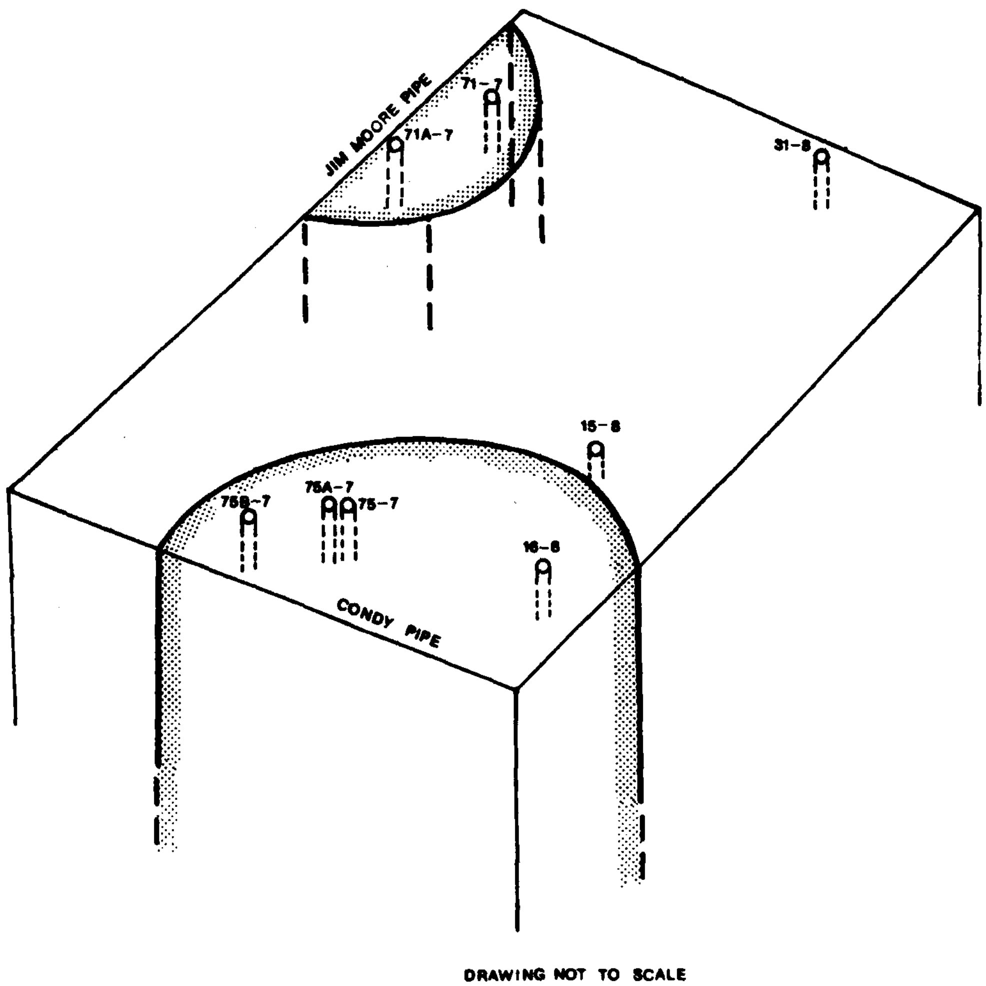


FIGURE 48. Sketch of the Results of Drilling Wells 75-7, 75A-7, 75B-7, 15-8, and 16-8. Establishes the edge of the Condy Pipe.

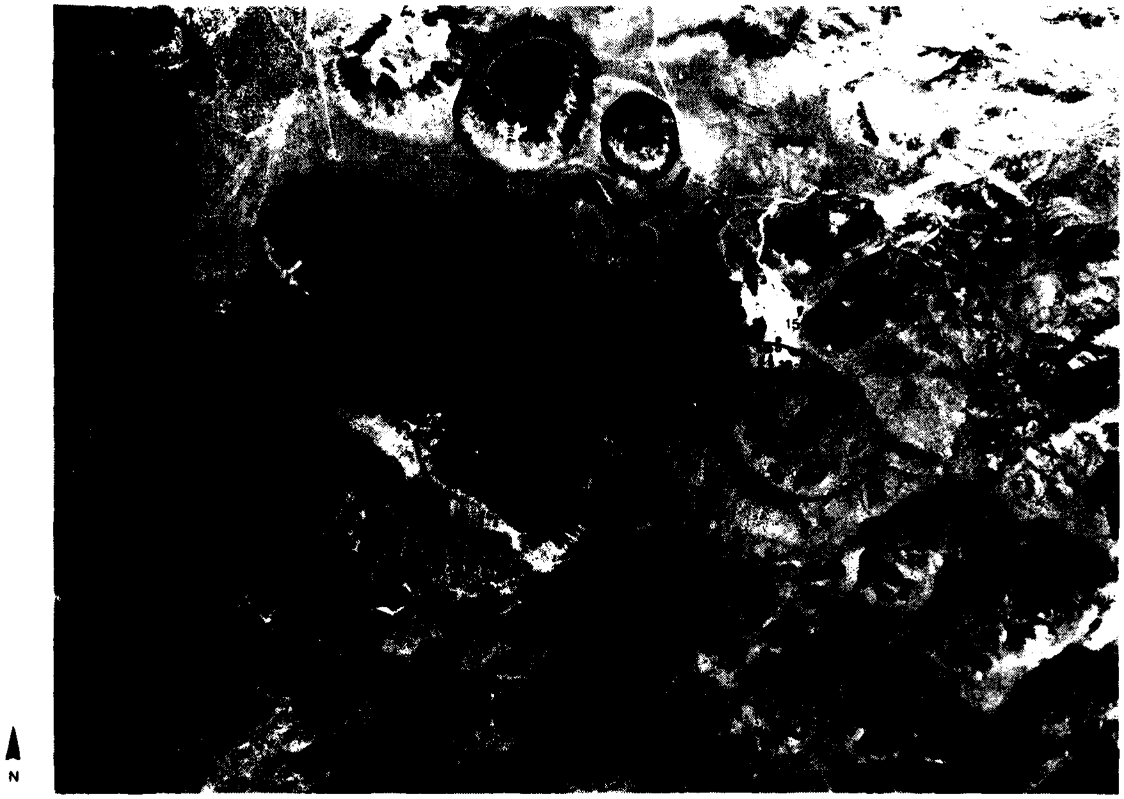


FIGURE 49. A Retouched Photograph of the Wells of Figure 48. Shows the prominent surface expression of the Condy Pipe.

FIGURE 50. Breccia Fragments Ejected From Well 16-8 on Start-Up. Note the subangular and slightly rounded nature of these chloritic fragments.

FIGURE 51. Vent or Breccia Pipe Surface Expression of the Jim Moore Pipe Tested by Wells 71-7 and 71A-7.

FIGURE 52. Coarse, Relatively Unaltered, Pink, Granitic Rock Expelled From Well 71-7 in Small Amounts on Start-Up. Rock contains minor chlorite and cubic pyrite.

FIGURE 53. White, Intensely Altered Sericitized Breccia Fragment With Cubic Pyrite. This fragment was expelled in large amounts from Well 71-7 on start-up and autobrecciated on pressure loss after leaving the well bore.

FIGURE 54. An Autobrecciated Rhyolite. Illustrates how the process can result in a considerable reservoir volume. (From an outcrop in the Creede Caldera system of Colorado.) (Lens cap is 2 inches in diameter.)

FIGURE 55. A Plot of Possible Explosion Breccia Pipes Present as Drilling Targets in the Coso Geothermal System. The main portions of the four nodal-controlled fracture patterns associated with the pipes are shown and the heavy dashed lines denote the axes of the zones of high ground noise in the area.

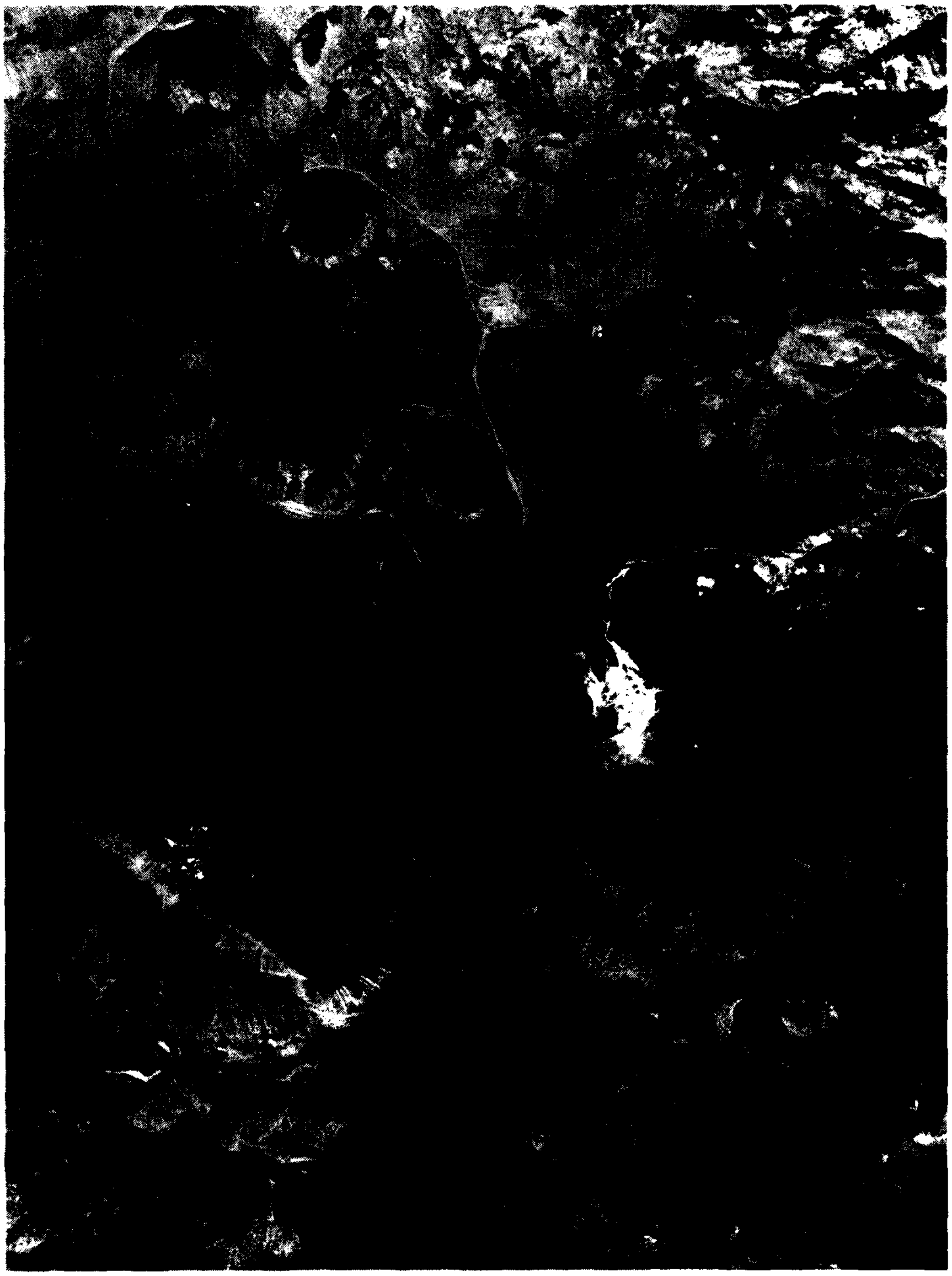


FIGURE 56. Perlite Domes. (A) The type of eruptive material associated with the Condy Pipe; (B) a similar dome but one that lacks a well-defined moat, though in this case it may be buried.

FIGURE 57. An Explosion Site With No Perlitic Extrusion, the Typical Signature of an Explosion Pipe.

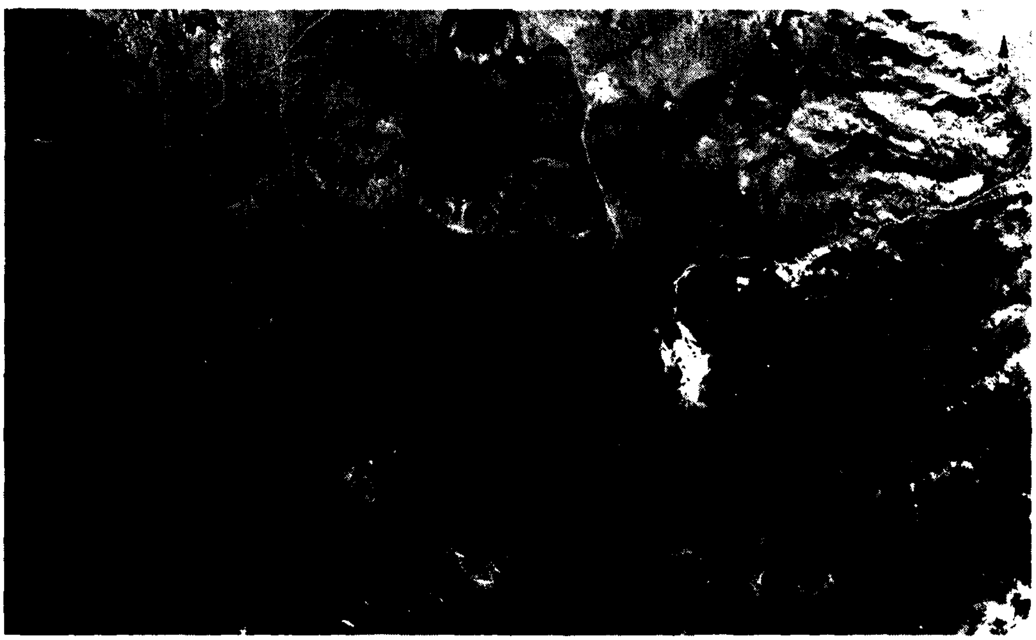


FIGURE 58. Typical "Lumpy Topped" Perlite Domes Most Numerous in the Coso Geothermal Area.

FIGURE 59. One of the Few Perlite Domes at the Coso Geothermal Area With an Open Crater.

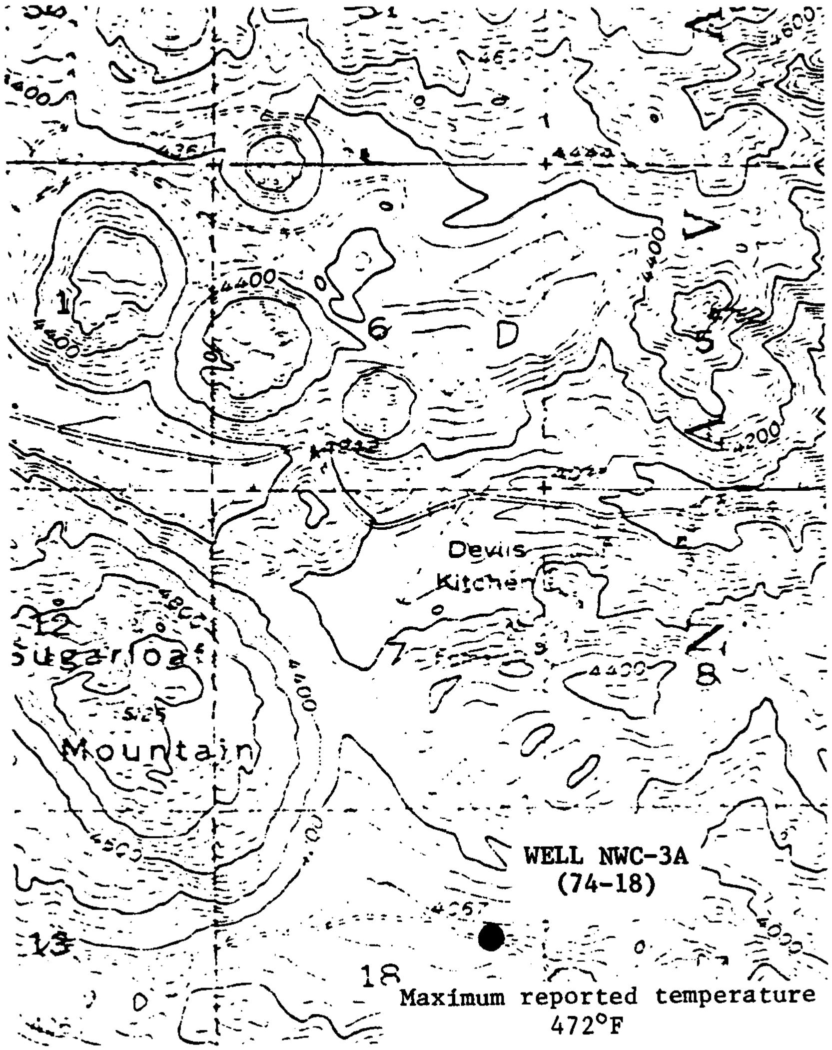


FIGURE 60. Location Map and Temperature Data for a Slim Hole Drilled Close to a Suspected Breccia Pipe.

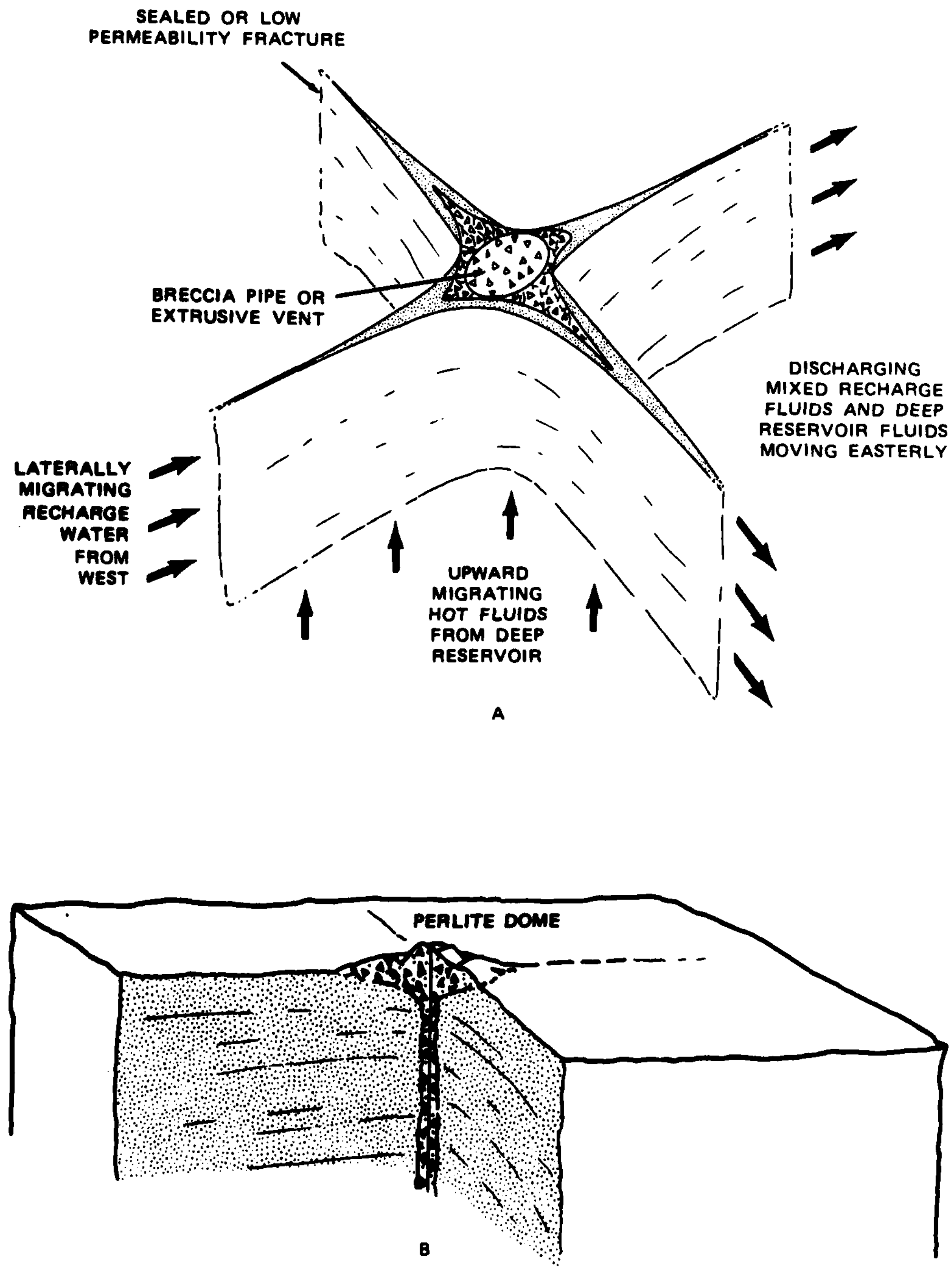


FIGURE 61. Fracture Intersection Type of Vertical Breccia Zone Reservoir Component.

FIGURE 62. Fracture Intersections Proposed as Drilling Targets at Coso.

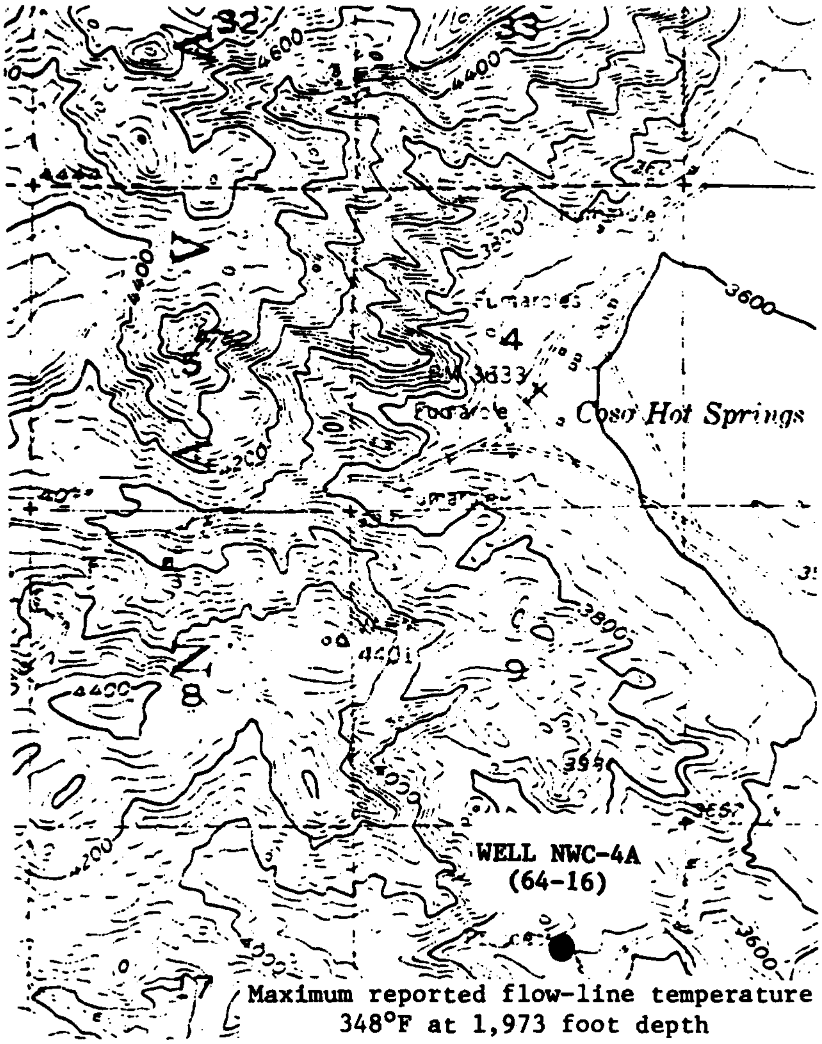


FIGURE 63. Location Map and Temperature Data for the Slim Hole Drilled Into the Fracture Intersection at the Wheeler Mercury Prospect.

FIGURE 64. Typical Targets of a "Suggestive" Nature. These may be tops of buried vertical pipes or fracture zone intersections.

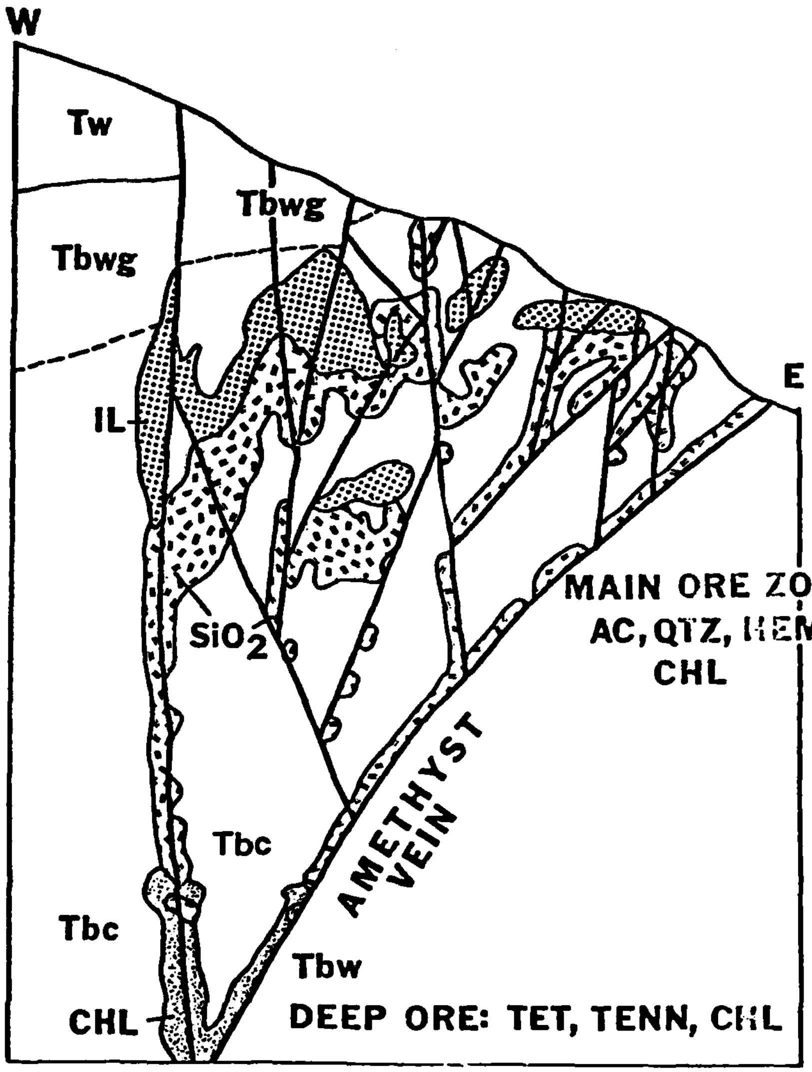
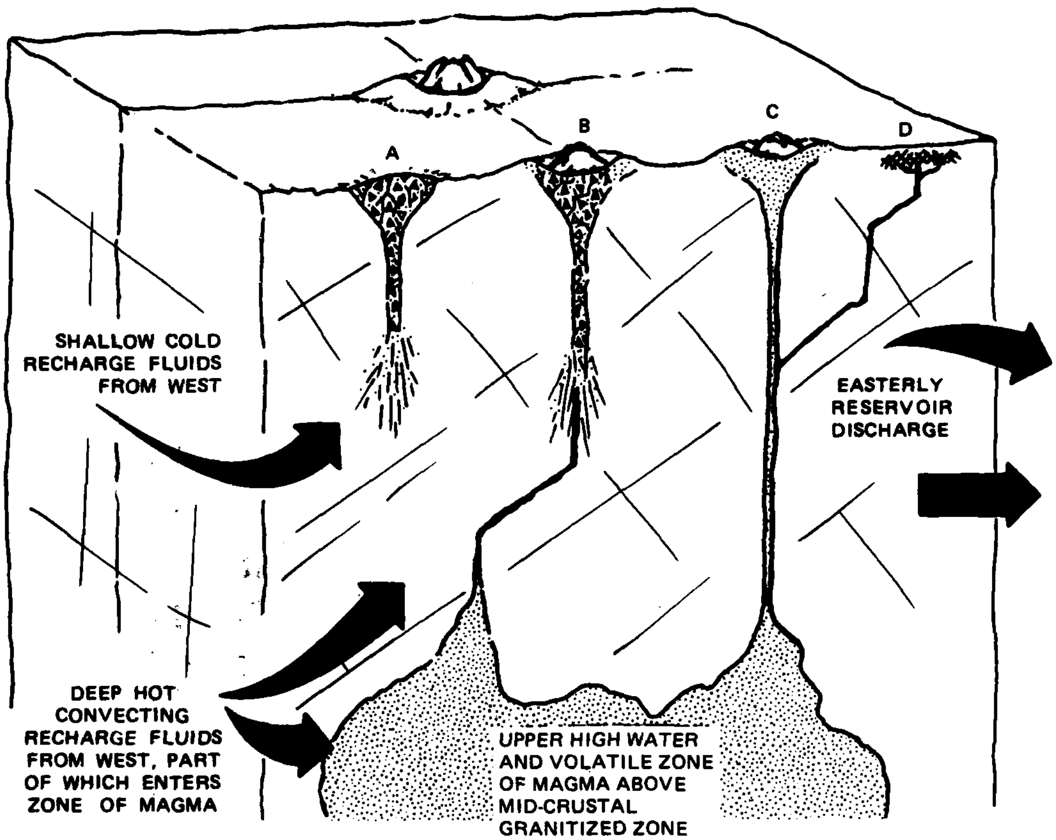


FIGURE 65. Idealized Cross Section of the Amethyst Vein Type of Spreading Fracture System. Adapted from Guidice by Cruson and Pansze as shown in Reference 35.



A. BRECCIA PIPE CONTROLLED BY FRACTURES, FRACTURE INTERSECTIONS, OR ZONES OF MICRO FRACTURING
B. COMPOSITE BRECCIA PIPE AND PERLITE DOME
C. PERLITE DOME
D. "SUSPICIOUS" AREA CAUSED BY NEAR–SURFACE DIKES AND/OR EXTENSIVE SHALLOW HYDROTHERMAL FLUID FLOW

FIGURE 66. Idealized Isometric View of the Authors' Present Model of the Coso Geothermal System.

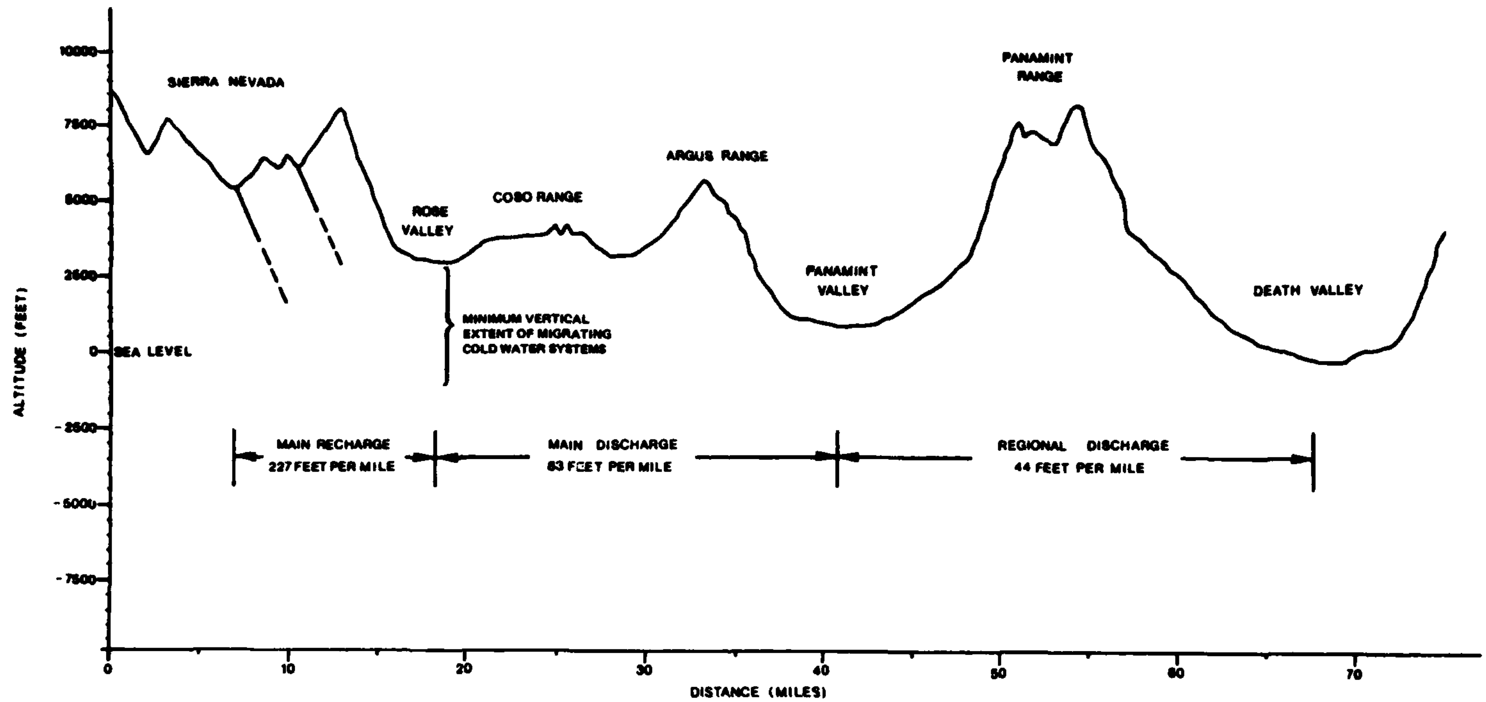
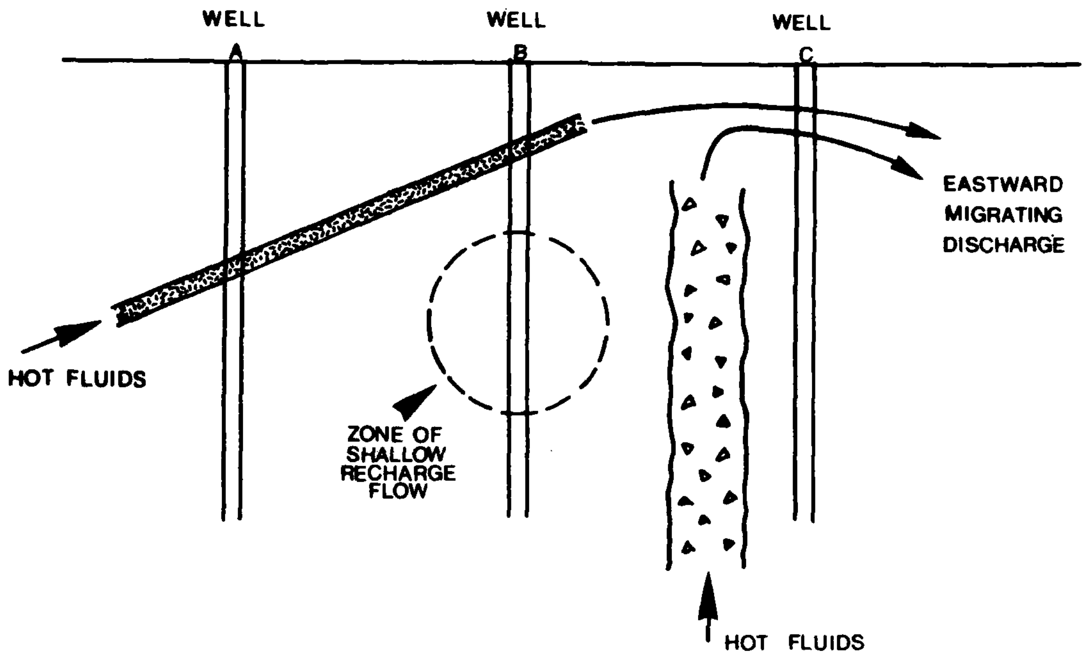


FIGURE 67. An Idealized Cross Section of the Sierra Nevada, Rose Valley, the Coso Resource Area, and Panamint Valley. Shows present-day hydraulic gradients and probable depth of the eastward migrating cold water systems.



WELL A - Local reversal as drill hole passes through active fracture.

WELL B - Local reversal as drill hole passes through zone of laterally migrating shallow recharge water (moving toward reader).

WELL C - Local reversal as drill hole passes through dispersal plume to one side of a fracture or breccia pipe.

FIGURE 68. Types of Geology at Coso That Give Numerous Localized Temperature Reversals. Adapted from Olpin, Tarlock, and Austin, 1979 (Reference 43).

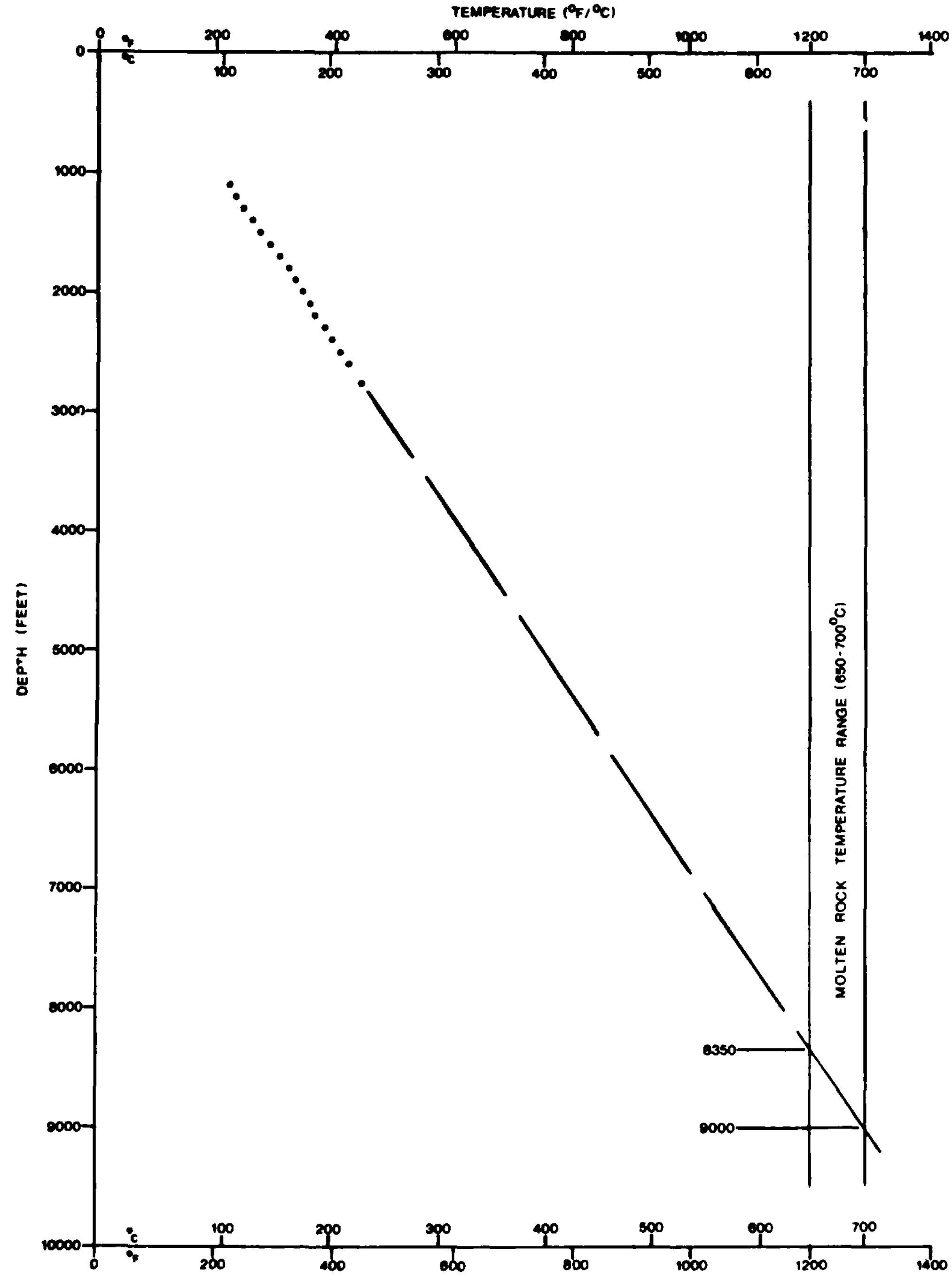


FIGURE 69. Temperature Data From Well NWC-1. Extrapolated to melting conditions as a probable lower boundary on deep drilling target conditions. (NOTE: Although recognizably a very deep extrapolation, the apparent depth to possible melting is supported by various unpublished and ongoing seismic data that show anomalous activity at depths of 2.5 to 3 kilometers.)

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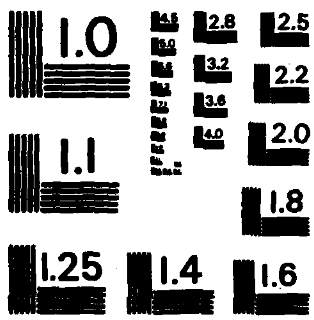

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1 Headquarters, U.S. Marine Corps (LFF-2)
1 Commander, Third Fleet, Pearl Harbor
1 Commander, Seventh Fleet, San Francisco
3 Naval Academy, Annapolis
    Director of Research (2)
    Library (1)
3 Naval Civil Engineering Laboratory, Port Hueneme
    Commanding Officer (1)
    L70PM, Dave Holmes (1)
    Technical Library (1)
2 Naval Energy & Environmental Support Activity, Port Hueneme
    Code 1101 (1)
    Code 111A (1)
1 Naval Postgraduate School, Monterey (Library)

3 Naval Ship Weapon Systems Engineering Station, Port Hueneme
Code 5711, Repository (2)
Code 5712 (1)
1 Naval War College, Newport
1 Headquarters, U.S. Army (DALO-TSE)
1 Chief of Engineers (DAEN-RDM)
1 Headquarters, U.S. Air Force (AF/LEYSF)
2 Air Force Academy, Colorado Springs
Code LGSF (1)
Library (1)
1 Air Force Intelligence Service, Bolling Air Force Base (AFIS/INTAW, Maj. R. Lecklider)
1 Civil Engineering Center, Tyndall Air Force Base (DEB)
1 McClellan Air Force Base (SMAL/XRE)
12 Defense Technical Information Center
1 Department of Energy, San Francisco Operations, Oakland, CA (J. Crawford)
1 United States Geological Survey, Menlo Park, CA (Library)
1 Associated Universities, Inc., Upton, NY (Brookhaven National Laboratory)
2 California Energy Company, Inc., Santa Rosa, CA
A. K. Carter, Administrative Manager, Compliance (1)
J. L. Moore, Vice President, Exploration (1)
1 Geothermal Resources Council, Davis, CA
1 Lawrence Berkeley Laboratory, Berkeley, CA
1 Los Alamos National Laboratory, Los Alamos, NM (Reports Library)
1 Oak Ridge National Laboratory, Oak Ridge, TN (Energy Division)
1 The Johns Hopkins University, Applied Physics Laboratory, Laurel, MD
1 University of Utah, Salt Lake City, UT (Department of Geology, Dr. J. A. Whelan)
1 University of Utah Research Institute, Salt Lake City, Ut (Earth Sciences Group)

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